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Working together to address global issues: Science and technology and sustainable development

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Nowadays the human community is facing many global challenges, such as food safety, water pollution and climate change. People have realized the importance of sustainable development. To tackle those global issues and to achieve the Sustainable Development Goals (SDGs) stated in the United Nations 2030 Agenda, joint efforts among countries around the world are necessary. All sides need to actively participate in global governance and contribute to the provision of public good in the international community. Science and technology is a field that deserves much more international cooperation. Scientific and technological innovation is the major driving force for social and economic development, especially for sustainable and green growth. This has been highlighted by China's President Xi Jinping on many occasions. He has noted that we should pursue innovation-oriented development, go green and pursue international cooperation in science and technology and building a strong talent pool.

Recognizing the close relationship between science and technology and sustainable development, we have produced a special issue to explore the roles of public scientific literacy, science education and scientific research in achieving sustainable development.

Advances in science and technology are inevitably accompanied by some social problems. Thus, a high level of scientific literacy among the public, including public engagement in and understanding of science, is important for the sustainable development of society.

Daya Reddy, president of the International Science Council, emphasizes the urgent need to enhance public scientific literacy in his article 'Scientific literacy, public engagement and responsibility in science'. First, students and the general public should be educated in a science-based way. The enhancement of the scientific literacy of the public can help prevent the rampant spread of false information and facilitate the application of scientific results. With public engagement in science, scientists' endeavours to achieve sustainable development can be more worthwhile and rewarding. Second, scientific knowledge and outcomes should be made accessible to policymakers, as they are the people who can make the most use of those scientific outputs. Without their support and dissemination, scientific progress cannot bring about large-scale benefits. To maximize the advantages brought by scientific development and reduce problems caused by the ignorance or misunderstanding of the public, scientific knowledge should not be limited to the scientific community; rather, it should be made accessible in a broader way, including for the general public, policymakers, students and future scientists.

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An effective way to address global issues is to equip students – the major driving force for future social development – with the knowledge and ability to tackle those problems. This means that, in the face of global challenges, science education has a distinctive role to play, which is illustrated in articles written by Robert A Kolvoord and Aurelio P Vilbar.

Kolvoord relates the United Nations SDGs to primary and secondary education in his article 'Fostering spatial thinking skills for future citizens to support sustainable development'. He notes that traditional, discipline-focused thinking might fail to achieve the SDGs, which are cross-cutting in nature. To solve this problem, we need innovation and disruption in primary and secondary school systems, which feature a monodisciplinary set of knowledge and tools, and we should equip students – the next generation of leaders and decision-makers – with the skills of geospatial thinking and reasoning. Kolvoord examines a particular educational programme for secondary students – the Geospatial Semester, which is intended to help students access and share data that bears on the SDGs and to enhance their abilities to cope with problems relating to the SDGs. The Geospatial Semester proves to be effective in improving students' spatial thinking skills and promoting a focus on the SDGs through the extensive application of geographic information systems in education. Therefore, he highlights the need to help the educational establishment to embrace such geospatial tools and the SDGs.

Vilbar also focuses on science education for sustainable development in his article 'Children as courseware collaborators: Using participatory research to produce courseware integrating science and sustainable development'. He notes that children – who will eventually be responsible for achieving sustainable development and who are the end users of the ESD (education for sustainable development) curriculum – are not actively involved in educational material development. Thus, in this research, Vilbar examines how teachers can collaborate with children to produce teacher-made courseware by virtue of participatory action research within the context of second-language teaching. He suggests that language curriculum and instructional material developers should develop contextualized digital materials in an interdisciplinary and customized way; this new way of producing courseware with students' participation can promote the learners' interest in science and ESD concepts.

Besides public engagement in science and science education, scientific research is obviously an indispensable part in our endeavour to achieve sustainable development. Science and technology plays a key role in dealing with global change and predicting and solving problems in case of emergencies such as natural disasters.

Fang Chen et al. discuss the contribution of science and technology to disaster risk reduction (DRR) in their article 'Building scientific capacity in disaster risk reduction for sustainable development'. DRR is crucial to the achievement of the SDGs in that the frequency and intensity of disasters increase as climate change intensifies and environmental degradation worsens. In the face of natural disasters, we need to focus on prediction and prevention, as well as response and recovery. To enhance our ability to cope with disasters, we have to thoroughly grasp the risks before making decisions and drafting policies. However, as Chen et al. note, the problem is that we lack such an overall grasp. Many countries and regions currently do not have easy access to relevant data, and traditional data sources prove to be inadequate for crafting effective and efficient responses and recovery options, let alone early preparation. To narrow the data gap, traditional data sources must be integrated with alternative and emerging data sources. Digital technologies, such as cloud computing, and infrastructure, including research programmes such as CASEarth, can provide valuable resources for multisource data integration, contributing to the development of information-driven policy and decision-support systems for DRR. Scientific researchers and policymakers should apply emerging technologies and data science methodologies to develop innovative solutions to global challenges and devise strategies for sustainable development, both within and beyond China.

The scientific community makes a tremendous contribution to the development of science and technology, but many scientists and their achievements remain unknown to the public. Thus, telling the scientific stories of the older generation may contribute to the public understanding of science and enhance people's respect for scientists.

Jianhua Lu, in his article 'On the role of global change science in sustainable development: Reflecting on Ye Duzheng's contributions', revisits the story of Ye Duzheng, a trailblazer of global change science in China. He reviews Ye's contribution to climate research and global change science in China and across the world. As a pioneer, Ye linked global change science to sustainable development, and his understanding and interpretation of orderly human activities merits more attention. Ye also stressed that public literacy in global change science and the interaction and cooperation among all kinds of science and all walks of life are essential to sustainable development. Ye's ideas have a lot in common with what scientists of the current generation are advocating. Reviewing the work of older scientists such as Ye Duzheng highlights the significance of their work and offers models for young scientists in their pursuit of scientific careers; moreover, it raises public respect for scientists and their contributions.

The realization of the SDGs requires joint efforts among scientists, educators, policymakers and the public. Science and technology, as a global public good, can directly or indirectly contribute to sustainable development. In an era of continuously emerging digital technologies, everything, including the solutions to global challenges, seems to be information driven. The cultivation of the next generation of scientists who shoulder the responsibility of sustainable development requires science-based and information-driven pedagogy. Disaster response and control, which are closely related to the SDGs, need information-based decision-making. In a word, to address global issues, all stakeholders should be equipped with a global vision and a science-based and information-driven pattern of thinking. The achievement of the SDGs requires international cooperation in science and technology, as well as collaboration among all walks of life and joint efforts within and beyond the scientific community.

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Article

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Scientific literacy, public engagement and responsibility in science

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Abstract
This work addresses the issue of scientific literacy and its connection to the responsibility of scientists in relation to public engagement. The points of departure are, first, the notion of science as a global public good, and, second, developments in the past few decades driven largely by the digital revolution. The latter lend a particular urgency to initiatives aimed at promoting scientific literacy. Arguments are presented for reassessing approaches to public communication. The particular example of genome editing is provided as a vehicle for highlighting the challenges in engagement involving the scientific community, policymakers and broader society.

Keywords
Ethics, public engagement, responsibility in science, science literacy, scientific literacy

1. Introduction

The word 'science' is derived from the Latin 'scientia', meaning 'knowledge'. It is an apt term to describe the endeavours and struggles through recorded history that have aimed at understanding the world in which we live, whether for its own sake or motivated by reasons of utility.

Scientific developments have taken place in fits and starts and have gathered momentum over the centuries, and the 20th century was characterized by an explosion in scientific progress. For some time now, scientific activity and progress have been dominated by professional researchers in universities and in public and private laboratories, and scientific research has become ever more specialized and sophisticated.

Science interacts with and influences the lives of individuals and communities. Dramatic progress has been accompanied by equally impressive applications, largely beneficial, although the use of scientific knowledge for harmful purposes is, as ever, a reality.

The question then is: to what extent is it desirable, or essential, that broader society become conversant with scientific knowledge, that is, be scientifically literate? A justification for scientific literacy as a pursuit might be motivated by reasons that include the utilitarian, the aesthetic and the cultural, and by a vision of society in which individuals and communities are well placed to weigh the

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impacts and consequences of scientific knowledge on their daily lives, health and safety.

This paper argues, first, that the nature of scientific and technological developments in the 21st century demands greater urgency in addressing the goal of promoting scientific literacy; second, that the social contexts that characterize this century should be a central consideration in shaping scientific literacy initiatives; and third, that it is a responsibility of the scientific community to be at the forefront of scientific literacy initiatives.

This work starts at the beginning, as it were, by considering what is meant by a scientifically literate individual or community. The link to scientific responsibility is made by examining the idea of science as a global public good: what is meant by this, and how it relates to scientific literacy. This leads naturally to an interpretation of scientific responsibility and the role of the scientific community in engaging in activities aimed at promoting scientific literacy.

The contemporary context in which the public learns about scientific developments is almost unrecognizable from that of a mere two to three decades ago. It is one that is shaped to a significant extent by the digital revolution, particularly by the explosion in information. It is important to understand this context, which is rich in opportunities for making science more accessible, but also fraught with developments that threaten the very basis of scientific literacy – for example, the propagation of pseudoscientific views and misinformation.

Scientific progress is often accompanied by ethical questions that might challenge cultural or religious norms. Citizens are best placed to consider their position on such questions when they have access to the relevant scientific background and details, presented in comprehensible fashion. These considerations apply as much to individuals as to groups in civil society, and to policymakers in government and elsewhere.

These contextual considerations provide the basis for the argument that the responsibility of scientists applies not only in communicating scientific knowledge beyond their own communities, but also in the manner in which public engagement is most effectively pursued. The 21st century context requires a reconsideration of the themes that are most urgent. The thread thus runs from science as a public good to the responsibility of scientists in promoting scientific literacy.

Complete trust in scientists is a foundational requirement for successful and enduring interactions between scientists and broader society. Although trust in science overall remains high, there are at any given time threats to such a trusting relationship, and the scientific community has a responsibility to ensure that it earns that trust by upholding the values of science and conducting itself in a responsible and ethical manner.

How then does one go about communicating with the public? The terms ‘public’ or ‘society’ take no account of the multidimensional and complex nature of the challenge. The relevance of science, and of scientific literacy, to society is brought into focus where scientific progress interfaces with cultural, social and religious norms and particularly when challenged by apparent tensions at those interfaces. An inability to recognize such complexity may well lead to efforts that turn out to be counterproductive. Thus, having reviewed the notion of scientific literacy in the 21st century context, it becomes important to set and act upon preconditions for successful engagements between scientists and society.

The objective of this work is to develop the themes referred to here in a systematic way, with an emphasis on the connections and interrelationships between scientific literacy and the responsibilities of scientists in relation to public engagement. The somewhat abstract development is reified by considering the particular example of genome editing, a truly 21st-century development that offers the promise of major benefits for humanity, yet one that is accompanied by serious ethical questions, the resolution of which must involve not only scientists and policymakers, but also civil society.

While the attempt here is to address issues of scientific literacy across a broad range of sectors of society, the major topic of scientific literacy at the school level and its intersection with science education lies beyond the scope of this work, and is not treated here.

2. What do we understand by scientific literacy?

The notion of scientific literacy refers in broad terms to the idea of scientific values, knowledge, discoveries and their applications, as well as the fundamental underpinnings of the scientific method, being familiar among the broader public. This aspiration carries with it a number of substantial questions: for example, what do we mean by 'familiarity'? How broadly should this knowledge be diffused within the general public? To what extent should sectors such as policymakers, public and private industries and NGOs be treated as entities through which specific, tailor-made scientific literacy initiatives are developed? And, how does one go about engaging with the public in order to convey scientific knowledge effectively and to achieve the desired ends?

It is useful to turn to some sources for comprehensive definitions of scientific literacy.

Holbrook and Rannikmae (2009) provide an overview of scientific literacy that includes a discussion of the range of definitions to be found. To fix ideas, the OECD PISA (Programme for International Student Assessment) framework defines scientific literacy as 'the ability to engage with science-related issues, and with the ideas of science, as a reflective citizen' (Organisation for Economic Co-operation and Development (OECD), 2019). It continues by describing as scientifically literate a person who has acquired the competencies to engage in reasoned discourse about science and technology, evaluate and design scientific enquiry and interpret data and evidence scientifically. Though the framework addresses school education, it provides sets of definitions and perspectives that are useful in the context of the focus of this work.

The corollary to such a definition is that a scientifically literate individual is in a position to draw on such knowledge in the course of participating in and contributing to debates of a cultural nature, as well as on issues that affect well-being at various levels: personal, family, community and nation.

What would one expect of a scientifically literate citizen? At a regional workshop for UNESCO's Project 2000+: Scientific and Technological Literacy for All (United Nations Educational, Scientific and Cultural Organization (UNESCO), 1993), scientific and technological literacy was defined as 'the ability to creatively utilize science knowledge in everyday life to solve problems'. The workshop materials described 17 'traits of a person considered scientifically and technologically literate', among which are the expectations that the scientifically literate individual

- Uses *concepts* of science and technology . . . in solving everyday problems and making responsible decisions in everyday life, including work and leisure;
- Engages in responsible personal and civic actions after weighing possible consequences of alternative options;
- Defends decisions and actions using rational argument based on evidence;
- Engages in science and technology for the excitement and the explanations they provide;
- Displays curiosity about and appreciation of the natural and human-made world (UNESCO, 1993).

Thus, the vision is of a society in which individuals, groups and communities, although not professionally trained as scientists, are in a position to appreciate the substance and beauty of scientific developments and draw on such knowledge in the course of contributing to decision-making processes that affect society as a whole.

3. The link to science as a global public good

The rationale for the promotion of scientific literacy may be self-evident, but it is important that it has a rigorous grounding. A point of departure for such a rationale is that of science as a public good. Public goods are defined as resources that are both non-excludable and non-rivalrous (Wikipedia, 2020). Non-excludability refers to the criterion that individuals cannot be excluded from the use of the resource or would not be required to pay for use. A public good is non-rivalrous in the sense that use by one individual does not reduce availability to others. Further, the good can be used simultaneously by more than one person.

The benefits of global public goods reach across borders, generations and population groups. Examples include fresh air, knowledge, lighthouses, national defence and flood control systems.

Take as a further example the eradication of smallpox: the whole of humanity benefits, both present and future generations. Success in responding comprehensively to the threat of global climate change would secure intergenerational as well as geographically widespread benefits.

Science is a global public good, an aspiration which, significantly, has been adopted as the vision of the International Science Council (2020a), a body whose stated mission is to serve as the global voice of science. The route from science as a public good to scientific literacy is determined by considering the implications of this vision for scientists and the corresponding responsibilities.

The scientific community has a responsibility, in the first instance, to disseminate scientific knowledge within its ranks, through journals and other specialist media, and in doing so to adhere to the editorial and ethical guidelines pertaining to the review, publication and assessment of such work. In exercising that responsibility, it is important that the great diversity of the scientific community be taken into account: the strength and depth of scientific systems and the extent to which they are properly resourced vary significantly. The spirit and the letter of science as a global public good therefore require that scientists take such variations into account to ensure that individuals and the scientific community have access to and participate in developments in science, regardless of their local circumstances: whether they are distant from and poorly connected to the loci of major activity, for reasons of geography or levels of economic development or whether there are factors such as gender or age that result in their marginalization.

The responsibility of scientists goes beyond dissemination within their own communities. There is a responsibility on the shoulders of the scientific community to ensure that scientific knowledge and results are made accessible in broader society, including the general public and policymakers. Furthermore, the mere dissemination of material that is inevitably specialist and technical in nature cannot suffice; the means by which such dissemination is carried out must take into account the target communities by ensuring that the information is not only accessible, but also comprehensible.

An understanding of the way science works is a prerequisite for successful public engagement. The effective dissemination of scientific information beyond the scientific community presupposes an understanding within broader society about the nature of scientific investigations, the provisional nature of scientific evidence, uncertainties in models and their interpretation and the process, generally complex with multiple paths, of arriving at consensus positions (Torcello, 2016; see, for example, Section 7 and, more broadly, the consideration of public communication strategies that seek to unite the ‘deficit model’ and ‘cultural cognition’ approaches, with climate change as the working model).

Scientific investigations are seldom straightforward, and errors do occur. A scientifically literate populace should have an awareness of these nuts-and-bolts aspects of scientific enquiry and of the various nuances of scientific research, and it is vital that scientists, for their part, do not paper over such imperfections and complexities in their engagements with the public. An open approach builds trust and better understanding, and makes for sustainable two-way engagements (International Science Council, 2020b).

This bedrock is especially relevant when the context for public engagement is an emergency or threat that has potentially ruinous and life- and livelihood-threatening implications for broad swathes of society, and in respect of which scientific advice is a central component of steps to combat the given threat. Recent examples would include the Fukushima disaster in Japan, the Ebola crisis in West Africa and the SARS-CoV-2 pandemic, an ongoing threat, the like of which has not been witnessed for more than a century. The response by governments to such threats necessarily includes, or should include, close collaboration with scientists. The resulting actions inevitably have a direct impact, sometimes devastating, on local communities, because of which scientists have a major responsibility to promote a good understanding of the scientific underpinnings of policy decisions and to ensure effective three-way communication involving scientists, society and policymakers.

4. The context in which public engagement takes place

The nature of public engagement and the objectives of scientific literacy are, to a great extent, shaped by the contemporary landscape of societal and environmental conditions as well as technological developments. This is no less true of the 21st century, which is witnessing the dramatic impact of what has been referred to as the digital revolution (Hodson, 2018): that is, the rapid growth of, and increasingly easy access to, computers of ever-increasing power and speed, accompanied by a similarly rapid growth in communication via online news media and various forms of social media.

These developments have irrevocably changed the circumstances under which news and information are communicated.

The ease of access to and the ability to participate in such communication is, of course, a good thing. Nevertheless, what might at first be regarded as a multiplicity of unalloyed benefits is accompanied by features that threaten to undermine the objective of sharing information that is honest, truthful and supported by evidence. Take, for example, the growth of the dissemination of manipulated, biased or fabricated information, lacking in editorial norms and processes for ensuring the accuracy and credibility of information. Communication via social media has ballooned, with high volumes, rapid communication and fact-checking being bypassed. Bots – software applications that run automated tasks over the internet – magnify the spread of fake news and contribute to items 'going viral'. It is estimated that more than half of all web traffic consists of bots (Lazer et al., 2018).

The term 'fake news' is understood in this context to refer to information that is deliberately, fabricated and often distributed in ways that mimic the formats of news media, thus lending it the appearance of credibility. There is an overlap between misinformation (false or misleading information) and disinformation (false information that is purposely spread to deceive people) (Lazer et al., 2018).

The widespread dissemination of fake news and misleading and biased information feeds new expressions of science denialism, casts doubt on the need for scientific understanding and interpretation and threatens evidence-informed decision-making in policy and public action. A significant proportion of such denialist interventions can be attributed to the industrial sector, primarily as a means of defending products such as tobacco and toxic chemicals (Michaels, 2020; Oreskes and Conway, 2010). It constitutes a fundamental – and potentially pernicious – attack on the public value of science, and in turn undermines efforts to build a robust global science system and to advance science as a global public good.

The dissemination of pseudoscientific arguments might be regarded as a subset of fake news, given features such as a lack of supporting evidence, erroneous arguments and a general incompatibility with the scientific method.

Furthermore, the politicization of some issues at the science–society interface has contributed to the emergence of 'post-truth populist epistemology' (Rosenfeld, 2018) and the adoption of ideological positions or anti-scientific stances on such topics as climate change, genetically modified organisms (GMOs) and vaccination that are diametrically opposed to and in conflict with the scientific consensus on these issues – all this through the use of sophisticated strategies to undermine the collective judgement and position of scientists.

The propagation of 'dissenting theories' (De Melo-Martin and Intemann, 2018) and related unscientific models and campaigns to discredit science pose a real threat to progress and are in conflict with the values of science and efforts to ensure the well-being of society. They require that scientists fundamentally re-evaluate their role in relation to broader society. The scientific community has the responsibility to be vigilant in the face of such anti-scientific acts, to make publicly known their lack of validity, and to advocate strongly for scientific values and the scientific method.

The nature of information flow during the SARS-CoV-2 pandemic provides a good example of challenges that are central to much of the digital age. There has been a deluge of information on the pandemic across various news and social media platforms. Some of this is based on good scientific practice, but a significant proportion falls under the heading of misinformation and is based on weak or no evidence or is deliberately misleading. Such misinformation is often interwoven with scientifically credible and accurate information, rendering it all the more difficult to identify trustworthy and reliable sources (Wasserman, 2020).

These developments all pose a fundamental threat to the integrity of processes by which science informs policymaking. They emphasize the importance of continuing engagement by the scientific community, which must maintain complete transparency and be explicit about both evidence-based information and potential shortcomings. They also give greater urgency to effective communication and engagement with society at large; a scientifically literate society is one that is in a better position to evaluate information and distinguish between items that have a genuine scientific underpinning and those that are pseudo- and anti-scientific in nature.

5. Public engagement and responsibility in science

Scientists have a role that goes beyond being mere brokers of scientific information within the scientific community. Consistent with the view of science as a global public good, the responsibility of the scientific community extends to communicating scientific information and results broadly, in civil society and among policymakers. There are, of course, significant challenges associated with conveying scientific information of a usually highly technical and specialized nature in a manner that renders it comprehensible to individuals who are not scientists. The link here to scientific literacy is clear: a scientifically literate person would be expected to have a sufficiently good understanding of the underlying scientific material to appreciate its beauty and ingenuity. Furthermore, where relevant, this informs their approach to making responsible decisions, whether in the workplace or as a private individual.

One would expect the means of public engagement to be directed also towards an understanding of the evidence that underpins the scientific results. That, in turn, presupposes a proper understanding of the scientific method: of the nature and role of evidence, and of what is meant by scientific consensus. These considerations are especially important in the present-day context of mis- and disinformation: the scientific community, as well as science communicators, have an especially important responsibility to ensure that the general public is well acquainted with the way in which science works, even if the arcane technical details are beyond any but specialists.

Similar considerations apply to the role of uncertainty in science. Scientific progress and discovery are replete with uncertainties in the interpretation of data and the extent to which a hypothesis stands up to scientific tests. Mathematical and related models are, by their nature, approximations of phenomena and should be open to robust testing and revision as necessary. Such an apparent lack of certainty, if not properly understood, may well engender mistrust or scepticism outside the scientific community. It is therefore important that the public gains a good understanding of those features of the scientific method in addition to being informed about scientific developments. Such a well-informed public is then equipped with the means by which to weigh up options for actions as individuals or as members of social and other groups, and to defend such decisions by appealing to the evidence and the means by which scientific consensus has been achieved. The role of scientists in this context lies well within the domain of advocacy: for the scientific method, and for arguments that underpin scientific consensus.

Much of the development that has taken place during the 20th and 21st centuries may be attributed to the use and application of scientific results. There is thus no doubt about the beneficial nature of science. Science also has harmful outcomes, intended or otherwise. The notion of dual-use research of concern captures this Janus-like nature of science. The term has been conceived in the context of life sciences research that is intended for benefit, but which might easily be misapplied to do harm (see, e.g. World Health Organization, 2013). Potentially harmful uses of science are present in most, if not all, scientific disciplines, in addition to residing in the means by which scientific information is communicated.

The domain of science advice lies at the interface of science and public policy formation, with the role of scientists being that of providing the scientific evidence and information relevant to the development of such policies. The role of scientists does not extend to that of advocating for one or another policy direction: in formulating policies, policymakers ordinarily take into account not only scientific input, but also a range of other considerations, such as public perception, timing and affordability. This particular arena of public engagement is a complex one, in which policymakers generally take advice from a range of sources that might include academies and formally appointed scientific advisers, as well as ad hoc advisory groups.

Whatever the make-up of the advisory cohorts, in the first instance trust in the scientific community by policymakers is essential. This is a *sine qua non* for robust discussion, for example, about the place and significance of science within the multifaceted forms of advice reaching the policymaker. A cautionary note on steering clear of anything that might resemble advocacy also plays an important role here in engendering such trust. Not the least complex aspect of this form of public engagement lies in the responsibility to present and interpret scientific material in a manner that allows its key aspects to be understood by a broad range of recipients, whose backgrounds are diverse and, in all likelihood, not scientific in nature.

The above issues have come to the fore most forcefully in conventional and social media from early 2020, with the unprecedented impact of the SARS-CoV-2 viral pandemic. The public has witnessed the role of scientists in advising governments, particularly the complexities of that role: diverse groups of scientists advising through formal and other routes, disagreement between groups of scientists on modelling the pandemic and its likely evolution, and measures to combat the spread of the pandemic and treat the seriously infected. This has been good, from the point of view of broader society, which has been able to witness first hand, as it were, the complexities of science advice in action during an emergency.

The impact of the pandemic, not only on the health of individuals, but also on social and economic aspects of their lives, will have brought home the importance of broader society being able to weigh up science advice and the responses of policymakers, and being able to identify instances of misinformation, deliberate or otherwise – although the latter is not straightforward even for scientists.

In addition to being better placed to engage with the immediate consequences of the pandemic, a scientifically literate society is one that is in a good position to also engage with its aftermath: plans for recovery, and for transformations – some of them no doubt permanent – that will inevitably follow. Policymakers would be better placed to manage and form policy in a context of uncertainty, with the need to weigh and synthesize advice from different specializations.

6. Trust in science

Complete trust in science and the work of scientists is a *sine qua non* for giving substance to the vision of science as a global public good. An implicit social contract requires that scientists uphold a set of scientific values, engage with integrity and honesty in their work, act ethically in a professional capacity and communicate scientific work with integrity, respect, fairness, trustworthiness and transparency. Both the beneficial and the harmful consequences of scientific knowledge and its applications should be communicated openly. Furthermore, in their engagements with policymakers, impartiality in informing policy is essential to engendering trust (Kofler, 2019).

That there are breaches of those ethical standards is clear from well-documented and reported cases of scientific misconduct (The Economist, 2013). Such cases threaten the reputation of science and efforts to engender trust and seriously compromise the lines of communication between scientists and broader society. Instances of misconduct include fraud, fabrication and falsification. A further problem is manifested by multiple reports of a lack of reproducibility (Brainard and You, 2018), which may or may not be a result of misconduct but which serve to undermine the ethical foundations of science if not addressed immediately, for example, through a retraction.

Reassuringly, there has been a rapid increase in actions taken by journals to identify cases of scientific misconduct and seek retractions where appropriate. The data shows a rise in the number of retractions since the beginning of the 21st century – a trend that has been attributed at least in part to more focused oversight on the part of journals – as well as an increase in the number of journals engaged in such oversight. It appears also that the number of retractions is slowing down, again possibly as a result of more rigorous review procedures on the part of journal editors. Such actions, as an example of regulation by the scientific community, serve to restore trust where it might have been undermined by the various practices of scientific misconduct (Brainard and You, 2018).

There is evidence to suggest that, notwithstanding the lapses in ethical behaviour on the part of a few scientists, the levels of trust in science remain relatively high and are on the increase, albeit with considerable variation by region and in relation to such factors as gender and socio-economic status (Wellcome Trust, 2019).

7. Communication

There is substantial variation in the extent of engagement with science within broader society. For example, understanding of the concepts of 'science' and 'scientist' has been found to vary from very high proportions in high- and some middle-income countries to much more modest numbers in low-income countries, although the issue is too complex to be reduced to a numerical proxy for levels of understanding of science. Furthermore, while a significant proportion of the world's population believes that science benefits them, there is substantial variation by region in the extent to which that belief is held (Wellcome Trust, 2019).

This provides some context that ought to inform initiatives aimed at communicating science beyond the scientific community.

The traditional view of science communication has been turned upside down by unprecedented developments in social trends. In the era of 'fake news' and the politicization of scientific issues, scientists and science communicators may well be regarded as partisan sectors having a particular ideological or political stance, rather than as conveyors of expert, evidence-based knowledge. This context demands a re-examination of the relationship between scientists and society and of approaches to communicating science to non-scientists.

An important component of communication about science relates to responses to the anti-science environment and the need for a vigorous defence of the scientific method, coupled with a creative and compelling articulation of the social, political, economic and cultural values of science. Scientists have a responsibility to ensure that policymakers and the general public are in a position to evaluate arguments in such a way that they can determine the difference between evidence-based scientific views on which consensus has been achieved and those that lack a scientific foundation.

The challenge, then, has as much to do with 'what to communicate' as with 'how to communicate'. The history of engagements between science and society features multiple examples of approaches by scientists that took no account of the social, cultural or religious contexts of communities. On the contrary, there are many examples of approaches that have rightly been labelled 'elitist' and have seriously undermined efforts at building a trusting relationship among scientists, broader society and policymakers (Lynas, 2018).

In engaging on controversial and politicized scientific issues, it is vital to respect feelings, moral intuitions and cultural contexts (Lynas, 2018), while being alert to the role of special interests that may serve to degrade public discourse. Merely repeating scientific opinions and outcomes, either more clearly or more loudly than usual, is not the way to success. Direct engagement with those outside the scientific community and a deeper understanding of how people receive and respond to messages both individually and collectively are vital. This requires leadership at the nexus of science education, communication and public outreach, sociology and behavioural sciences (for an exploration of these and other issues related to the public communication of science and technology, see, e.g. Schiele, 2018).

Scientists are motivated to make major discoveries but may be reluctant to engage in communication outside their particular communities. They may, often with justification, feel ill-equipped to engage in such communication. This highlights the precise nature of the scientific community's responsibility with regard to communication: rather than it being the responsibility of every single scientist to be an active and effective communicator, the interface with the public and policymakers is a communal responsibility and decisions about the means of communication and of those scientists who engage in such communication should be guided by criteria that ensure that competent, if not gifted, communicators are in the vanguard of such work.

Like most other enterprises, scientific work – whether research, teaching or outreach – is accompanied by incentives and rewards for work of high quality. These considerations are relevant in approaches to engage in communication: beyond monetary reward, recognition in universities and research institutions of the value of such work and its relevance should be considered when scientists are hired or considered for promotion.

The communal responsibility extends also to the need to forge links and sustained relationships with various forms of media, whether through science journalists or otherwise. The dilemma that scientists face is one of a deluge of information through formal and social media. There is a need to surmount the relevant obstacles to ensure that scientific news of interest and importance to the general population is granted space in this crowded environment. Unless strong, enduring relationships are established with individual journalists, editors and others, communication through the media is patchy, lacking in visibility, and will ultimately fail to reach the target readerships in the numbers expected.

8. The relevance of a scientifically literate population to societal development: The case of genome editing

For a more concrete perspective on issues relevant to science and society, consider the example of gene and germline editing – a dramatic scientific development that promises major benefits but one which also poses serious ethical questions.

The year 2012 saw the advent of CRISPR, a powerful tool for transforming a bacterial immune system into a fast and versatile genome editor that can alter DNA sequences and modify gene functions (Vidyasagar, 2018). The method has multiple actual and potential applications: in medicine, for example, in treating genetic defects; and in agriculture, in developing drought- and disease-resistant crops (Lallanilla, 2019).

The advent of CRISPR has been followed by a multiplicity of applications and an explosion of further scientific work and accompanying publications, as well as patent applications. While the highest number of publications are from the United States, China is a close second – a development that can be linked to substantial government investment in new facilities and ambitious research projects (Cohen, 2019a, 2019b, 2019d). In particular, researchers in China publish twice as many CRISPR-related agricultural papers as those in the United States.

There has also been some controversy, arising from the widely reported news that a researcher had carried out a clinical application of CRISPR to edit the genes of an embryo so as to render it immune to HIV (Cohen, 2019c). That has been condemned in the scientific community as an instance of serious scientific misconduct.

The regulation of genome editing is still in its early stages, in which work on crops leads the way, partly because such research presents fewer risks and ethical dilemmas than medical applications, such as genetically engineering animals for transplanting organs. Nevertheless, there is some way to go with regard to developing appropriate regulations in the domain of agriculture. For example, a European court has made CRISPR subject to the same stringent testing conditions as GMOs (Ledford, 2019). On the contrary, the United States Department of Agriculture exempts genome-edited plants from regulations covering GMOs as long as the editing is carried out by inducing mutations that could have occurred naturally and not by transferring DNA from other species. Most of the world has no specific regulations covering CRISPR-modified food (Cohen, 2019c). The matter continues to be hotly debated.

This is the situation that confronts not only the scientific community, but civil society at large as well as policymakers at national and supranational levels. It exemplifies the urgent need for carefully constructed and comprehensible engagements with broader society.

The urgency lies at the very least in the substantial ethical issues involved in gene editing, and more particularly germline editing, as the latter would allow characteristics to be passed on to future generations. It involves ethical and societal issues of which the general public should be aware, notwithstanding the technical and scientific complexities: Are we crossing a red line because of the possibility of altering our species? What are the views in broader society that would be central to considerations entertained by policymakers, on eugenics-like goals: designer babies with superior intelligence or sporting abilities? What are the margins of safety in carrying out CRISPR-based interventions, for example, if DNA cuts are made in the wrong place?

While there is some way to go before regulatory frameworks are implemented to cover much, if not all, of the globe, some current initiatives are worth noting. A committee has been set up by the World Health Organization to examine the scientific, ethical, social and legal challenges associated with human genome editing (World Health Organization, 2020). Also, the US National Academies and the UK's Royal Society have reported on the work by a commission convened to 'develop a framework for scientists, clinicians and regulatory authorities to consider when assessing potential clinical applications of human germline genome editing, should a society conclude that heritable human genome editing applications are acceptable' (US National Academies, 2019).

9. Concluding remarks

There is an understandable expectation that success in addressing major challenges requires unprecedented levels of cooperation between scientific communities, across the natural and social sciences, along with policymakers and, crucially, civil society. These considerations apply equally to such challenges as climate change, the agenda captured in the Sustainable Development Goals, and the SARS-CoV-2 pandemic. A necessary, though by no means sufficient, condition for success in meeting those objectives is a society that is broadly scientifically literate, has an understanding of how science works, and one which can participate in processes that shape policies and programmes that affect people's lives.

The 21st century brings with it significant and unique challenges to efforts aimed at the promotion of scientific literacy. However, its potential benefits for broader society are massive and unprecedented: a better understanding of the impact of scientific developments on health and well-being, the ability to engage knowledgeably on issues at the intersection of science and cultural norms, and to share in the enjoyment and excitement that accompany scientific discovery.

Author's note

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Article

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Fostering spatial thinking skills for future citizens to support sustainable development

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Abstract
The United Nations Sustainable Development Goals (UNSDGs) represent the consensus of the global community on the most important issues facing our planet. A major challenge is embedding the UNSDGs in primary and secondary education and providing the tools needed for students to explore and analyse data relevant to the UNSDGs. The Geospatial Semester is a secondary school class in the United States that is focused on mastering geospatial technologies and using them to examine key problems of student interest, including the UNSDGs. Research studies show that the extended use of geographic information systems augments student problem solving and spatial thinking skills, particularly for females. Spatial thinking skills are a key gateway to science, technology, engineering and mathematics careers and an avenue to addressing the UNSDGs.

Keywords
Geospatial technology, secondary education, spatial thinking, sustainable development

The United Nations Sustainable Development Goals (UNSDGs) (United Nations, 2015) provide critical guidance for making our world more just and equitable. The level of interest in, and activity surrounding the goals suggests that they are galvanizing the attention of people in countries across the world, and there is substantial discussion about how to bring the goals more centrally into national educational systems (Commonwealth Hub, 2017).

However, many of these efforts are informed by very traditional, discipline-focused thinking. The cross-cutting nature of the goals makes it very difficult for them to be addressed with a monodisciplinary set of knowledge and tools. There is a clear opportunity for innovation and disruption in primary and secondary school systems to bring about new approaches to address ‘wicked’ problems like those in the UNSDGs.

Technology has a major role to play in augmenting our educational pedagogy, specifically geospatial technology. These technologies allow students and teachers to visualize the impact of location on the UNSDGs and assess the affordances and challenges of place. Geospatial technologies continue to evolve dramatically and have become ubiquitous tools for decision-makers in almost all industries.

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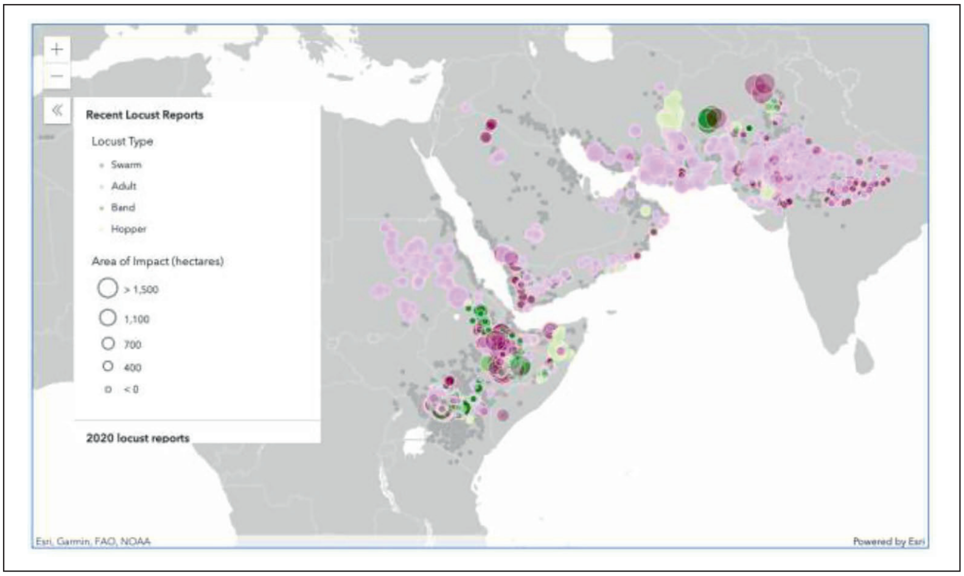

Figure 1. Map showing the concentration of desert locusts, courtesy of the Sustainable Development Solutions Network.
Source: 'Locust Hub', Food and Agriculture Organization of the United Nations, https://locust-hub-hqfao.hub.arcgis.com/, captured 20 July 2020.

However, their diffusion and use in primary and secondary classrooms have been much less impactful.

In this article, I discuss a spatial approach to education and to teaching the UNSDGs. I support the approach using examples from the research literature and share a variety of examples of student work. I also note the impact of the use of geospatial technologies on student learning. The article concludes by discussing the challenges and opportunities of using such an approach to meet the educational challenges of the UNSDGs.

1. The United Nations Sustainable Development Goals

The UNSDGs are almost a decade old, arising in their current form at the Rio Summit in 2012 and replacing the prior Millennium Development Goals.[1] The UNSDGs broaden the focus beyond poverty, education and health in the developing world to focus on the need to sustain our planet while providing for equity across nations. The UNSDGs create a blueprint for the sustainability of our environment, our health and well-being, our families and our institutions.

While the SDGs cover the full range of human endeavours, there is a unifying theme in understanding our progress and challenges: geography. Analysing the UNSDGs and our progress in meeting them requires an approach that crosses national borders and allows us to look at the goals at a variety of spatial scales, from state/province to nation to region to continent to planet. This kind of approach requires a variety of geospatial tools, including remote sensing and geographic information systems (GIS), to acquire and analyse the data needed to assess our progress. In fact, the Sustainable Development Solutions Network recently introduced a new website and portal[2] that features geospatially driven dashboards to assess global progress on the SDGs.

For instance, when assessing the size of the food-insecure population or the fraction of the world's population living in extreme poverty, there are clearly spatial patterns and strong correlations between goals (e.g. poverty and education). Figure 1 shows an example of one of the spatial dashboards.

In this map, the scourge of desert locusts is displayed, showing the areas where they occur in large concentrations. In these areas, local farmers and communities are under severe stress to provide adequate food supplies for already food-insecure populations. Maps such as these provide decision-makers with the information they need to attend to incipient crises and to develop pathways to sustainable outcomes, ensuring that the UNSDGs can be met.

Clearly, the leaders of today see geospatial tools as a critical element in sustaining our planet, but what about the leaders of tomorrow?

2. Spatial thinking and science, technology, engineering and mathematics education

As we consider how to help the next generation of leaders and decision-makers develop geospatial thinking and reasoning skills, it is important to note that spatial reasoning skills are a critical element of success in science, technology, engineering and mathematics (STEM) careers.

Research by Wai et al. (2009), based on a longitudinal study over many decades, shows that individuals in STEM careers have higher spatial thinking skills than those in other careers (including teaching). However, this has not led to a strong focus on spatial thinking in primary and secondary curricula around the world (National Research Council, 2006; Newcombe, 2017), in spite of the fact that research shows that these skills are malleable and students can improve (Uttal et al., 2013), sometimes by substantial amounts. In fact, a report by the US National Academies states that ‘Spatial thinking is presumed throughout the K-12 curriculum but is formally and systematically taught nowhere’ (National Research Council, 2006). This ‘tragedy of the commons’ is unfortunate, as it means that no one subject in a secondary school has responsibility to foster spatial thinking or GISs.

This lack of attention to spatial skill building, coupled with the lack of a large-scale introduction of geospatial technologies in primary and secondary education (Baker et al., 2015; Milson et al., 2012), leaves our current students ill-prepared for the work of attaining and monitoring the UNSDGs. However, there are a number of promising efforts to bring more geospatial technologies into curricula and provide students with the experiences they need to add these tools to their problem-solving arsenal.

3. Geospatial technology

Given the importance of spatial thinking in preparing those pursuing STEM careers and the central role that geography plays in the UNSDGs, it would be ideal to find a way to combine geography and technology in primary and secondary education. Geospatial technologies, such as GIS, meet this need and offer students an avenue to build their geographical understanding by analysing real data. In this paper, I examine a particular educational application of this technology: the Geospatial Semester.

The Geospatial Semester is an award-winning programme for secondary students in the United States wherein students learn about the use of GISs through applications to a variety of problems (including UNSDGs). It culminates in an extended project of each student’s choosing that requires them to specify the problem, gather relevant data, analyse those data and create a compelling presentation of their results (Kolvoord et al., 2019). Students can also earn college credit from James Madison University for their efforts. Inaugurated in 2005, more than 5000 students have participated in this programme in the last fifteen years.[3]

Figures 2 to 4 show example projects to provide a sense of the range of student interests.[4]

As the projects in Figures 2 to 4 show, the students are drawn to topics that are centred on the UNSDGs, particularly Goal 6 – Clean Water and Sanitation, Goal 7 – Renewable Energy, Goal 11 – Sustainable Cities and Communities and Goal 13 – Climate Action. They are able to create compelling pieces of research using geospatial technologies and communicate their findings to key stakeholders. In fact, Geospatial Semester students often work with external stakeholders as they do their projects, including local, state and national government agencies, non-governmental groups and private companies. Geospatial Semester students are learning by doing, developing real-world experiences with data and technology that lead them into

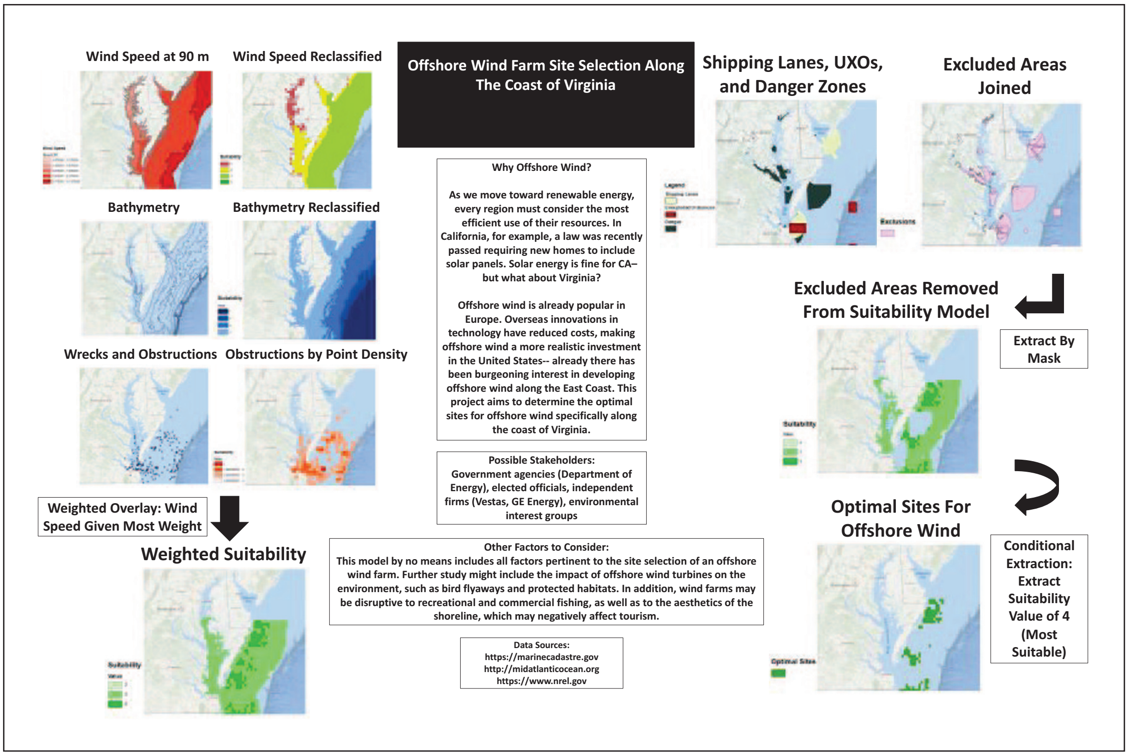

Figure 2. A project exploring possible factors in siting offshore wind turbines off the east coast of the United States.

higher education in a number of fields, including geography. However, does this work impact their spatial thinking skills?

4. Spatial thinking and the Geospatial Semester

Through assessing student work with the Geospatial Semester, including the rich array of student projects, our team began to wonder if the use of GIS was making any difference in either their behaviour or their cognition. Like many other GIS in education projects, there were abundant anecdotes but little quantitative data. In order to develop a rigorous set of studies, we collaborated with psychologists at Northwestern University and Georgetown University. We conducted an array of studies to explore the impact of the Geospatial Semester on participating students and compared their performance with students who had not taken the Geospatial Semester.

In each study, we recruited students taking the Geospatial Semester class and similar students (same age, academic level and academic performance) not taking the class. In each study, we saw improved performance on a number of measures. We saw clear evidence of '21st century thinking skills' (Charles and Kolvoord, 2016) in students' final projects. We also saw an increase in the use of spatial language and problem-solving skills (Jant et al., 2019), specifically in arguing from evidence and reasoning through a study that used video interviews at different points in the school year.

The most complete study combined behavioural and cognitive measures to examine the performance of Geospatial Semester participants and a comparison group chosen by using propensity score matching that assigns a 'match' from the non-Geospatial Semester students based on gender, academic performance and other demographic measures. This allows for a robust comparison group since a control group study is not possible in this setting.

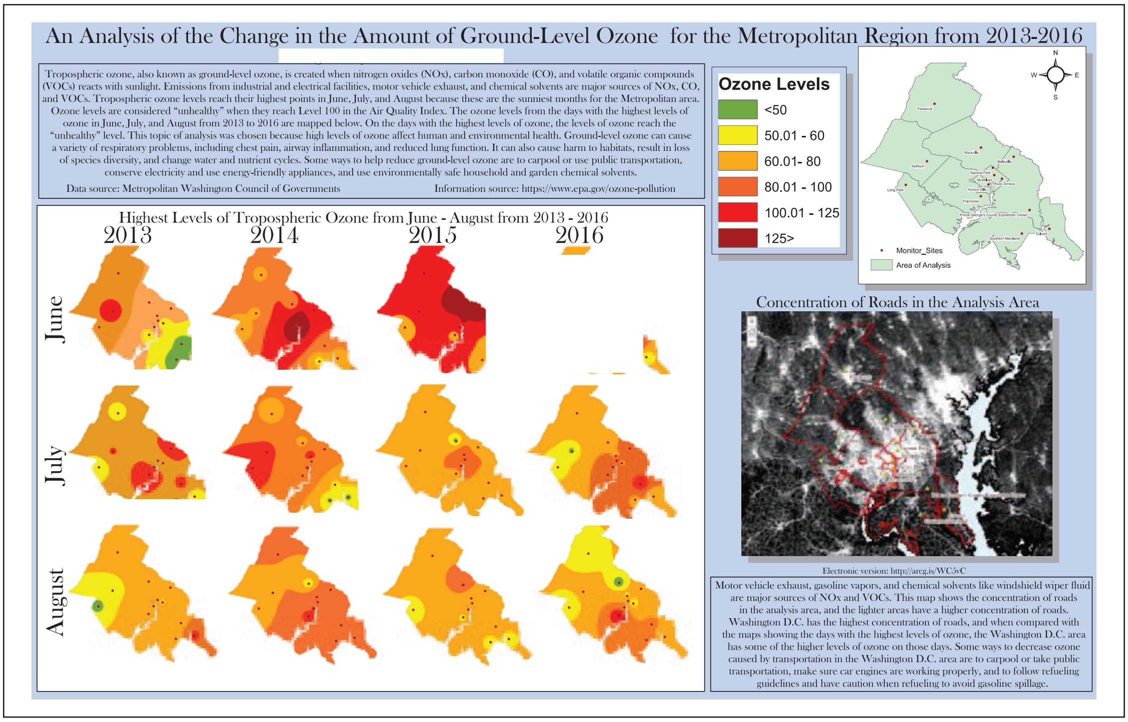

Figure 3. A project exploring ground-level ozone concentrations, a marker of air pollution, near a large city.

In the behavioural measures, we saw improved efficiency in different spatial thinking measures (Mental Rotation Test and Embedded Figures Test), with a stronger effect for female students (Peterson et al., 2016). We also saw confirmation of the problem-solving findings from the study discussed above (Hollenbeck, 2019).

Along with the behavioural studies, we also conducted a cognitive study taking both Geospatial Semester students and comparison group students to the fMRI Center at Georgetown University and conducting brain scans. Although we are still in the process of analysing the data, preliminary results suggest that Geospatial Semester students show greater recruitment of spatial parts of the brain for non-spatial tasks and a stronger impact for female students (Cortes et al., 2021).

We were also able to explore parental attitudes towards students pursuing spatial careers (Muenks et al., 2019); the impact of student participation in spatial activities as youth and adolescents on spatial thinking skills (Peterson et al., 2020b); and the likelihood of pursuing a GIS course based on prior experience with GIS (Peterson et al., 2020a). Across all the studies, we saw a positive impact from pursuing the Geospatial Semester and an improvement in student spatial thinking skills, potentially opening opportunities for the pursuit of STEM careers.

5. Spatial thinking and the Sustainable Development Goals

The results obtained from students undertaking the Geospatial Semester suggest that the extended use of GIS can both augment student spatial thinking skills and promote a focus on the UNSDGs. The use of geospatial technology promotes the asking (and answering) of interdisciplinary questions that make up the UNSDGs in a way that standard curricula simply do not. The promotion of spatial thinking (and the possible opening of STEM careers) is a useful by-product. There is real opportunity in connecting GISs and the UNSDGs for students.

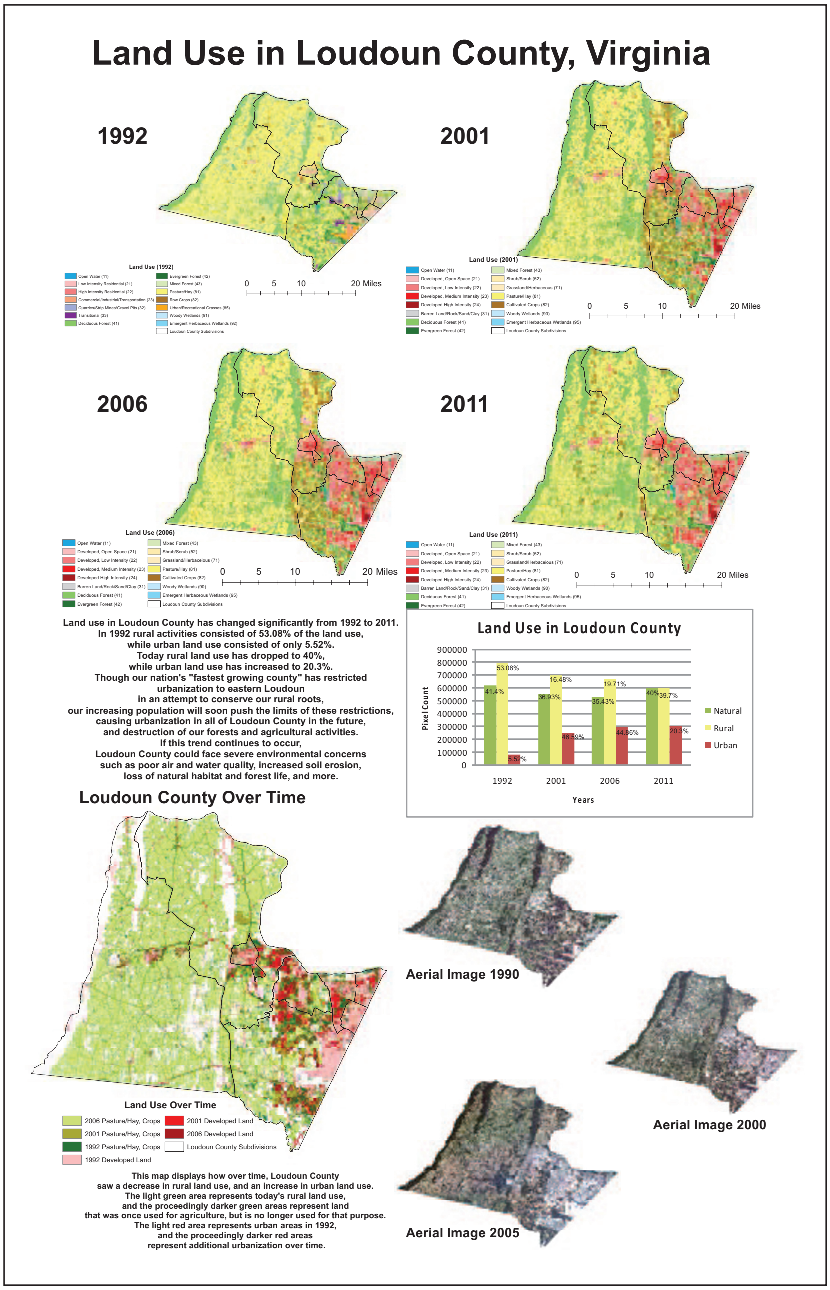

Figure 4. A project exploring the changes in a once rural area that has seen substantial development over the past 20 years due to its proximity to a large American city.

However, despite the many affordances of GIS use in secondary classrooms, a number of challenges arise. Teacher preparation programmes do not include any focus on either spatial thinking or geospatial technologies. In fact, in the United States, the UNSDGs often merit little attention. This is largely driven by a very siloed curriculum that is not easily shifted. In addition, computer access and technical support can be very uneven across schools.

As the UNSDGs gain more currency in education, geospatial technologies will continue to be a viable tool for analysis, visualization and communication. The growing ease of use of GIS, including a strong focus on mobile applications will level the access barrier and allow more classrooms to engage. Hopefully, societal pressures will more deeply infuse the UNSDGs in school curricula around the world.

6. Conclusion

We have shared an important technology application to facilitate secondary students in their work addressing the UNSDGs. Through the use of GIS, students can access and share data that bear on the SDGs. They can conduct analyses to understand global progress towards the UNSDGs and communicate their results with a variety of stakeholders. The continuing evolution of GIS promotes cloud-based collaboration and the integration of mobile data collection and sharing applications. This represents a tremendous opportunity for our students, but we will need to help the educational establishment embrace the tools and the UNSDGs. Even small steps could lead to significant progress around the world. We need to give students access to data and give them hope that we might one day meet the UNSDGs.

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Notes

1. See the background of the UNSDGs at: https://www1.undp.org/content/seoul_policy_center/en/home/sustainable-development-goals/background/.
2. See https://www.unsdsn.org/.
3. More information on the Geospatial Semester is available at https://www.isat.jmu.edu/geospatialsemester/.
4. More student projects can be found at https://www.isat.jmu.edu/geospatialsemester/recognition.html.

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Article

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Children as courseware collaborators: Using participatory research to produce courseware integrating science and sustainable development

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Abstract

UNESCO's 2014 report on education for sustainable development (ESD), *Shaping the Future We Want*, shows that there have been worldwide advances in integrating ESD into school curriculums. Although there is a global curriculum in ESD, children as the end users of the curriculum are not actively involved in constructing sustainable discourses. Cognisant of children's role in materials development, this research investigates how teachers can collaborate with children in producing teacher-made courseware using participatory action research (PAR). The study was conducted with 37 teachers enrolled in a graduate course on second-language teaching. Its goal was to produce courseware that promotes ESD and science concepts, such as global warming and the environment. Using PAR, the children collaborated with the teachers in designing the content. Interviews, focus-group discussions and surveys show that the courseware promoted excitement, science and ESD concepts, but suggested revising and trimming some videos and reading texts.

Keywords

Education for sustainable development, participatory action research, content-based instruction, English-language teaching

'Do not call us future generations when we are excluded in reality! In this age of climate crisis, we are the concerned party who has no rights (authority) but has to take all the responsibilities.' (Kim, 2019) This was the paradoxical outcry of the young people of Seongdaegol Community, Dongjak, Republic of Korea, who helped educate the community on energy conservation through the Seongdaegol Energy Saving Movement (Kim, 2019). In this movement, adolescent village students analysed energy consumption and worked collectively with the community on their project Do-It-Yourself Mini-Solar Prototype. Through this assignment, solar lights were installed in community childcare and senior citizen centres and reading rooms.

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The success story of Seongdaegol proves that children and other young people are not just consumers of knowledge but also active producers in constructing a sustainable world. It showcased a multidisciplinary approach, applying science, technology, public relations and education to promote sustainable energy consumption. The project manifests the goal of education for sustainable development (ESD), which is to transform society by helping people develop knowledge, skills and behaviours needed for sustainable development (UNESCO, 2014b). Von Braun (2017) stated that education should not be guided by human capital formation for lifelong learning in the utilitarian market but for the recognition of children as contributors to the development of a sustainable society.

The case of Seongdaegol is not, however, a reflection of how ESD is being implemented in the curriculum worldwide. Although there are successful examples of ESD integration in the curriculum (UNESCO, 2014a), in pedagogy and curriculum development (Laurie et al., 2016), and in building the capacities of sustainability leaders (Franco et al., 2019), the participation of children as the end users of ESD has not been widely exploited in curriculum and materials development (Donovan, 2016). Donovan highlighted that children could collaborate with adult researchers on sustainability issues. Unfortunately, if children participate in curriculum and instructional materials planning (Shamrova and Cummings, 2017), their participation is only in the first phase and they are often disengaged during the data analysis process. This implies that the views of children as collaborators and end users in the development of instructional materials have been silenced.

To promote more learner-centred instructional material, this research addressed the recommendations of Zhao et al. (2017) and Dell (2018) to use participatory action research (PAR) in developing ESD- and science-based interactive multimedia courseware (IMMC) in teaching Grade 8 students. Zhao et al. and Dell emphasized that curriculum developers need to use PAR to listen to the critical opinions and experiences of the children as users of and collaborators on the material. PAR is a dynamic research process that promotes dialogue and conscientization between the researchers and the participants as end users of the materials being developed (Balakrishnan and Claiborne, 2017; Danley and Ellison, 1999).

Conducting PAR with children can help in customizing instructional materials because the materials used in the classroom and in teacher training were designed by specialists who may have the subject-matter expertise but lack the localized socio-educational context (Mulà et al., 2017). In the Philippines, teacher training usually follows a top-down, one-shot, cascading model in which the curriculum and materials are designed by national or regional offices (Lomibao, 2016; Oracion et al., 2020). PAR with children can contextualize such national or regional materials because it can connect theory and practice in participation with the respondents, who can offer practical solutions to problems (Reason and Bradbury, 2012). According to the UNESCO report on ESD (UNESCO, 2014a), participatory learning processes and problem-based learning are effective methods in ESD curriculum and materials development.

1. Content-based instruction

The method of using ESD and science concepts in English-language teaching is anchored in content-based instruction (CBI), which uses academic content in language teaching (Snow, 1998; Wesche, 2012). Considered to be content-enriched, CBI has been widely used to promote a dual commitment to language and content learning, such as sciences or ESD, to support the diverse needs of language learners (Stoller, 2004). In CBI, the content taught in English classes is non-language subject matter or topics that are closely aligned with other school subjects. These topics (e.g. recycling, geography) become the springboard in discussing linguistic, cognitive and metacognitive skills, as well as subject matter that students need in order to succeed in their learning endeavours (Stoller and Fitzsimmons-Doolan, 2016).

CBI is also deeply grounded in the societal mission of education. Sato et al. (2017) held that, since the ultimate mission of education is to promote a sustainable society, students' criticality should be nurtured by teachers who encourage critical engagement with 'language' and 'content' texts on various global issues. They stressed that content to be used in language teaching should take a sociocultural turn and have connections to other academic fields, education at large, and society.

In the courseware, science and ESD concepts were the obligatory content in teaching competencies in the English language. Topics on global warming, the environment, food security, cultural diversity and gender equality were used as a springboard in learning English vocabulary, appropriate verb tenses, subject–verb agreement and other grammatical knowledge. Videos on global warming and climate change were used as viewing text to develop children's competency in making conclusions and generalizations. News articles about peatlands in Indonesia and global carbon footprints were used as grammar exercises in using the active and passive voices.

Using such authentic science texts promotes meaningful learning among the students and avoids the idea of teaching English for no obvious reasons (Jordan, 1997). Substantial studies show that CBI is effective in promoting language performance, content learning and communications (Garner and Borg, 2005; Laviosa, 2020; Pessoa et al., 2007; Stoller and Fitzsimmons-Doolan, 2016).

2. The English for Sustainable Development Project

This paper is part of a bigger project called the English for Sustainable Development Project, which aims to create a collection of IMMC to be used in teaching English as a second language to Filipino children. The courseware addresses the need for the revised junior high school English curriculum of the Philippines' Department of Education to produce instructional materials that promote multiliterate, multimodal, inter/multidisciplinary and sustainability education (Department of Education, 2016).

The new Philippine curriculum aims to develop digital literacy by drawing on informational texts and multimedia to build content and language knowledge, especially in viewing competencies. However, the technological support for education in the country has been more focused on providing computer infrastructure and integrating technology in the curriculum with teachers' professional development (Tomaro and Mutiarin, 2018). The production of localized IMMC has not been a priority. Thus, language teachers may have been adapting context-free but accessible global texts in teaching viewing competencies (Vilbar and Ferrer-Malaque, 2016).

The courseware topic for this study is ESD, which aims to integrate values, activities and principles of sustainable development in education to respond to the world's social, economic, cultural and environmental problems (Liimatainen, 2013; UNESCO, 2007). The goal of ESD is to improve the quality of life for all citizens of the world (UNESCO, 2018).

As a limitation, the courseware focused on 7 of 17 themes from the United Nations Millennium Development Goals: environmental conservation and protection, sustainable production and consumption, health promotion, overcoming poverty, gender equality, cultural diversity and intercultural understanding and peace (SEAMEO INNOTECH, 2010). The themes imply an inter- and multidisciplinary approach but rely heavily on science concepts, especially in the areas of global warming, climate change, disaster management and sustainable food consumption.

3. Research objectives

This research investigated how teachers can collaborate with children in producing teacher-made IMMC using PAR. The study was conducted with 37 Filipino teachers enrolled in a course in the Master of Education – English as a Second Language degree programme. The goal was to produce courseware that uses science and ESD topics in teaching grammar, reading and viewing competencies.

Using PAR, Grade 8 students collaborated with the teachers in designing the content, immediate feedback and graphical user interface (GUI).

This research answers two questions: (1) How are science and ESD concepts integrated into English-language teaching IMMC? (2) How did the participation of children help in the development of IMMC content and GUI?

4. The participants

This study involved three kinds of participants: (1) 37 graduate school students, who were in-service teachers; (2) students of these teachers; and (3) my high-school students. Some teachers did not have classes when the pilot testing was conducted, so they requested that my students be their participants.

The in-service teachers were my students in graduate courses on second-language teaching. The courses were divided into three parts: second-language teaching theories and principles, courseware development, and pilot testing. The teachers used the authoring software Author Plus Pro from Clarity English (Hong Kong).

To meet ethical requirements for research, all of the teachers were consulted before the research was conducted and were given an alternative to create printed instructional materials if the courseware production was deemed to be too complicated. They all gave their consent to publish their courseware output, reflections and survey results during their pilot testing with their students. The courseware output and survey results were part of the course requirement, while the reflections were not graded. After the consultation, the agreement was included in the course syllabus and approved by the Graduate School Coordinator of the university. It was also stressed that teachers had the option of not continuing to produce the courseware if the task became too difficult.

For the Grade 8 students of the 37 teachers, their participation in the pilot testing was voluntary and not graded. The teachers provided them with laptop or desktop computers to use and to evaluate the courseware at their convenience. To protect the privacy of the teachers and students, pseudonyms are used in this paper.

Neither the teachers nor I own the copyright of some videos and reading texts used in the courseware, which is used only for research and not for commercial purposes. All sources were correctly acknowledged.

5. Methodology

As part of a larger research project, the courseware's syllabus was developed through consultations among teachers, English-language curriculum experts and students. The syllabus was validated and published in a conference proceeding (Vilbar and Ferrer-Malaque, 2016).

This paper focuses on children's participation as collaborators in developing the courseware during the pilot testing and initial implementation. The pilot testing aimed to determine the children's views on the courseware's content and exercises before the formal implementation of the IMMC in the school. To gather data, it used an open-ended questionnaire, semi-structured interviews and focus-group discussions.

The open-ended questionnaire aimed to determine the extent to which the science and ESD concepts used in the courseware developed students' interest in learning the texts, promoted ease in reading and viewing, and were used in completing the exercises. It also determined whether the GUI and layout made it easier for students to complete the IMMC exercises. As supplementary data-gathering procedures, the semi-structured interviews aimed to determine the users' experience in using the courseware. The interview questions focused on the readability of the printed and video texts, on words that hindered reading, and on the topics of and time required for the reading and viewing materials.

The focus-group discussions aimed to validate the users' summarized answers in the open-ended questionnaire and semi-structured interviews. The teachers facilitated the discussions in groups of 5–10 students. Each student expressed their views on the following questions:

- Which of these ESD and science texts are the most or least interesting?
- Which are the most easy or difficult to understand?
- Which questions are the most easy or difficult to answer?
- Which of the tests require the most or least thinking time?

6. Results and discussion

This section presents the results of the participatory process between the teachers and the students in designing the courseware. It presents the courseware syllabus, the sample science- and ESD-based reading texts and exercises, and the evaluation of the IMMC in the pilot testing and initial implementation.

Table 1. Salient points of the courseware syllabus.

Lesson	ESD theme	Science content	Language competency	Essential question
1	Environmental conservation	Peatlands in Indonesia	Identifying cause and effect	What are the effects of burning peatlands on the atmosphere and the fishing community?
2		Windmill invention of William from Malawi, Africa (electricity)	Giving predictions	What are the effects of the windmill invention on the community?
3		Using solar panels (electricity)	Identifying cause and effect	How can solar panels be beneficial for people and the environment?
4	Disaster and risk reduction management	Global warming	Getting the main ideas of news and feature articles	How did global warming submerge the island?
5	Cultural diversity	Preparation of halal food	Summarizing texts	How is halal food being prepared?
6	Health promotion	Calorie counting	Noting important details in informative videos	How can calorie counting benefit your body?

6.1. The courseware syllabus

The courseware is versatile: it can be used either in stand-alone instruction or in computer-aided instruction with the teacher. It is used via desktop or laptop computers.

The courseware's syllabus is divided into two modules: the 'Viewing to Reading Modules' and the 'Grammar Modules'. The modules follow this sequence: (1) Objectives, (2) Lessons, (3) Exercises and (4) Assessment. The content of the modules, which is related to ESD or science concepts, is shown in the sample syllabus in Table 1. The table highlights only the salient parts of the content.

As shown in Table 1, Lesson 1, the news video about peatlands in Indonesia is used as the content in teaching the language competency of 'identifying cause and effect'.

As shown in Figure 1, students read the definition of peatland and 'guide' questions about why peatlands are burned. Then, they click on the video to watch and answer the questions. As shown in Figure 2, students answer a vocabulary comprehension exercise focusing on the effects of burning peatlands on wildlife and other inhabitants of the area.

In Lesson 2, the speech of the teenage windmill inventor, William from Malawi, Africa, is used to teach the objective 'giving predictions' and as a reinforcement activity for the lesson on 'identifying cause and effect', as shown in Figure 3. In this exercise, students analyse the parts of the windmill that produce wind power and the amount of electricity generated for William's village.

One topic appealing to children is about a mystery island. As shown in Figure 4, students read a news article about New Moore Island, an island of which both India and Bangladesh claimed ownership. However, global warming ended their dispute by submerging the island, according to the article. After reading the article, students answer reading comprehension questions.

As shown in Figure 5, students watch a news report about a public school in the Philippines that used solar panels. Then, as a viewing comprehension exercise, the students discuss the benefits of solar panels for the school and the environment.

From the syllabus and sample exercises, it is evident that CBI is a holistic pedagogy in teaching English grammar, reading and viewing competencies while also teaching the ESD themes and the science concepts of peatlands, greenhouse effects, carbon emissions, renewable wind and solar power, and climate change. The syllabus promotes a dual commitment to the learning of English language structures (Stoller, 2004) in 'identifying cause and effect', using the content of peatlands in Indonesia.

The IMMC is anchored in the assertion of Eli et al. (2020) that the use of an interdisciplinary approach in

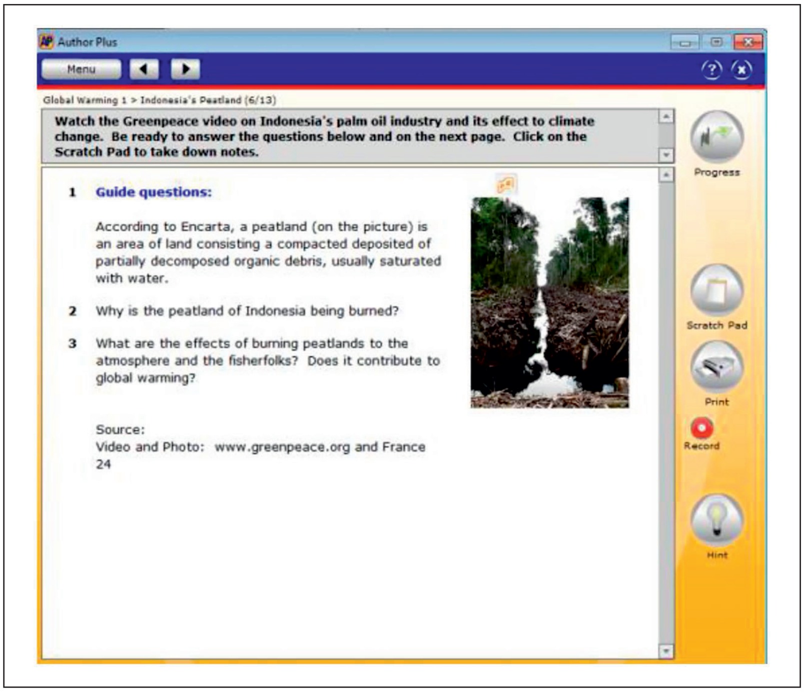

Figure 1. Viewing exercise: cause and effect of burning peatlands.

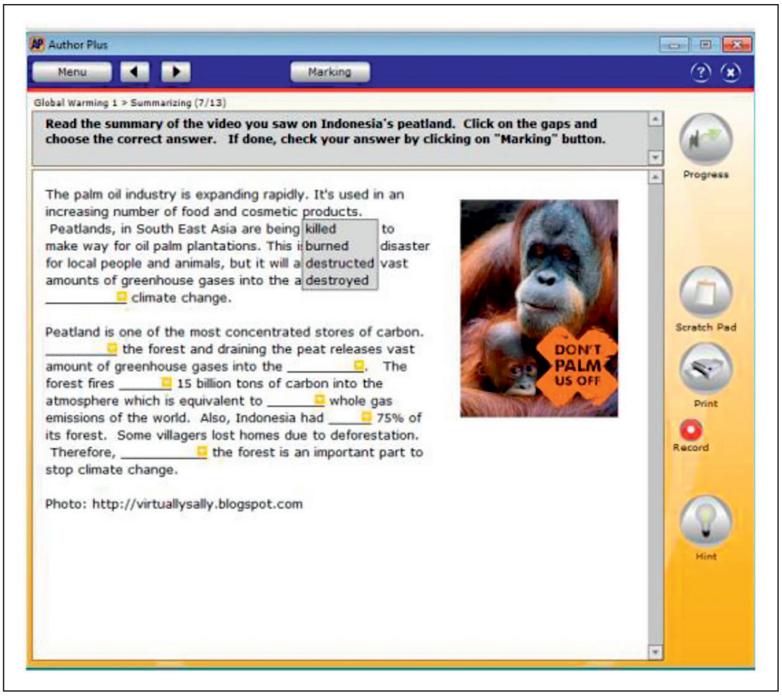

Figure 2. Vocabulary building: effects of peatland burning.

Figure 3. Viewing comprehension: windmills as a source of renewable energy.

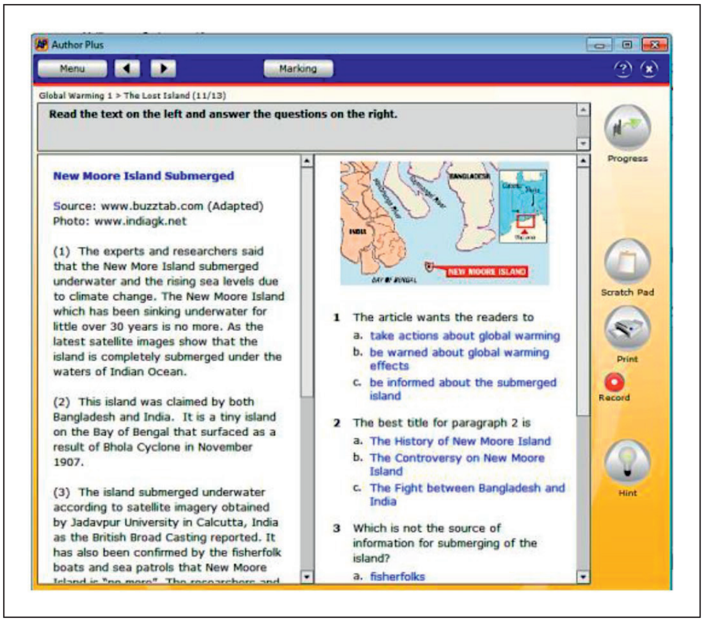

Figure 4. Reading comprehension: effects of climate change on small islands.

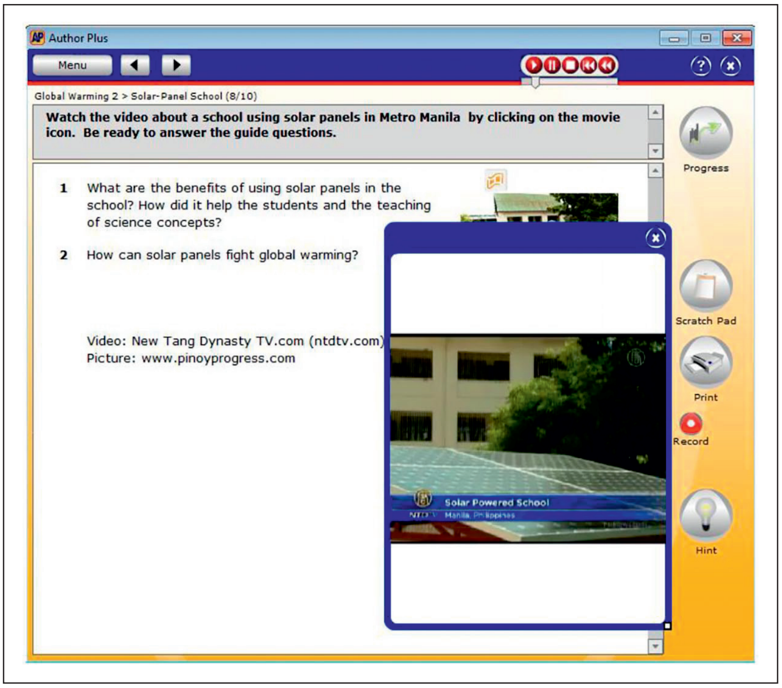

Figure 5. Viewing comprehension: effects of solar panels.

teaching ESD across a range of subjects promotes a more holistic understanding of sustainability. It develops a seamless discussion of a sustainability issue – from the basic problem of global warming to the sustainable solution of using solar power. The courseware translates the ESD theories into practical pedagogical application and orients the students towards their larger responsibility for creating a sustainable future (Sato et al., 2017). It allows the students to critically reflect on texts and videos on sustainability issues.

6.2. Children's participation in courseware development

In the pilot testing, the students used the courseware and shared their experiences via interviews, focus-group discussions and surveys to improve the courseware's content and GUI. The GUI is the interface of the courseware that allows users to interact with the computer through direct manipulation of various graphical elements and visual indicators such as menus, icons and navigation buttons (Jylhä and Hamari, 2020).

6.2.1. Improvement of the content. Through this new experience of developing courseware and collaborating with the children, the teachers felt enthusiastic about measuring the opinions of the students. Findings from the interviews, focus-group discussions and surveys show that the children displayed more excitement towards the viewing lessons than towards the reading texts. This could be attributed to the novelty of using IMMC in teaching. For the video content, the majority of the children claimed that the lessons on the environment, cultural practices and women's empowerment were educational, interesting and informative. The following excerpts demonstrate their evaluation:

> Student A: 'Articles provide information about the current status of security around the globe. The courseware taught me that we should not waste resources.'

> Student B: 'I learned how important cultures are. Nowadays, the rate of cultural preservation sank because of modernization. The courseware preserved cultures by reading and viewing articles.'
>
> Student C: 'I know the effects and disadvantages of global warming. We should reduce our release of carbon dioxide . . . which can damage our resources.'
>
> Student D: 'The courseware voiced out the role of women to our society. Women hold crucial roles in the development and destruction of a society. When women are given the right to education, then they can create a better future.'
>
> Student E: 'I learned more about El Niño and La Niña in the courseware.'

The children approved of the video content and considered it essential to create a sustainable world. Some shared their dismay about malnutrition and poverty around the world but were curious about various global indigenous practices and sports. Their excitement about learning with videos demonstrates the ability of multimedia to enhance student learning and digital skills (Schmid and Petko, 2019), student engagement and learning (Coyne et al., 2018), motivation and learning (Liao et al., 2019), and positive attitudes towards learning (Alsalhi et al., 2019).

Although the participants claimed that the reading lessons promoted relevant information about sustainability, most of them considered the assignments to be boring, tiring and long. Many of them suggested using shorter reading texts. However, the experience validated studies that have found that reading on paper promotes better reading comprehension than reading on a computer screen (Kong et al., 2018; Støle et al., 2020).

What was rewarding about the collaboration with the children was their honesty and integrity about the science content. They felt that reading articles on global warming or solar power was a boring experience but that watching videos about climate change was educational. This conflicting reality made us realize that offering the same topic using different modalities can yield different levels of comprehension and appreciation. For example, the children preferred viewing a scientific video about a carbon footprint to reading about it.

This experience added to our understanding of materials development that integrates science concepts, especially in terms of selecting the mode of content delivery. The alignment of video content and instructional design to learning outcomes is a complex process (Bétrancourt and Benetos, 2018) that needs more investigation. Digital reading has fewer benefits than paper reading when the reading materials are informational texts (Delgado et al., 2018). In the courseware, most reading materials were categorized as informational texts, such as those discussing sustainable food consumption and calorie counting, peatland burning and greenhouse gas emissions.

These types of texts develop global and scientific knowledge but are considered cognitively demanding and require active reading strategies (Mariage et al., 2019; Santoro et al., 2016). This process of improving the courseware content through children's participation proves the importance of participatory learning processes in creating ESD materials (UNESCO, 2014a).

Some recommendations from the children were not fully followed due to the required learning competencies that the courseware needed to achieve. For example, putting subtitles on all videos was not done because some of the videos were designed to develop the required competency of 'note-taking of events' or 'vocabulary'. The teachers and I agreed to put subtitles on videos that required a strong and technical science background and on videos that used unclear language. For instance, the video on global warming that focused on carbon emissions statistics had a subtitle to promote the scaffolding of the science-based topic.

This decision conforms with the findings of Pujadas and Muñoz (2019), who concluded that embedding subtitles in videos depends upon the language competence of the students to comprehend the video and the goal of the instruction. The subtitles can help both the students and the English-language teachers to understand the technical context and jargon of the topic. Furthermore, they can promote reading ease and appreciation of the lesson rather than explicitly discussing all the jargon before, during and after watching the video.

6.2.2. Clarifying the level of difficulty. As adults, teachers may have different experiences or schemas of the content's level of difficulty. The children's participation helped to clarify the viewing and reading content's levels of difficulty, familiarity and interest. For example, at first, the teachers were uncertain about including a video commercial featuring Thai football players who lived in a fishing community. The video had a message of diversity, but all the dialogue was in Thai, so it could not promote competence in oral English fluency. However, when it was shown to the students, all of them were happy to watch the video. When they were asked to summarize the video, they could recall in English the elements of the plot.

What the teachers perceived to be difficult or complex was proven otherwise by the children. This experience demonstrates the beneficial effects of PAR in materials development. PAR allows the narratives and feelings of the children to be heard in courseware development (Dell, 2018; Zhao et al., 2017). It empowers the end users and participants to decide on the materials they will learn (Balakrishnan and Claiborne, 2017; Danley and Ellison, 1999).

The children also stated that the article on the Kyoto Protocol was interesting but too difficult to appreciate. They said that the words were mainly jargon that was difficult to understand in one reading. When the teachers and I reviewed the article, we realized that it was too technical because of its sociopolitical–legal nature. This difficulty in reading sustainable development texts is common in internationally produced ESD materials (Kioupi and Voulvoulis, 2019). This could be due to the nature of the texts, which have sociopolitical undertones that are context dependent.

To improve the article, the teachers subjected it to readability testing and revised some words into understandable English without sacrificing the content. We also added a pre-reading activity that focused on the technical terms and their definitions.

The teachers' action of revising the article shows that PAR can transform material to make it more learner centred and comprehensible to promote a wider appreciation of the content by the end users. Listening to the critical opinions of children as collaborators enhanced the ESD IMMC (Dell, 2018; Zhao et al., 2017). In response to the children's sincere comments, the text was revised to match the students' cognitive level, and a pre-reading exercise was created to promote scaffolding. This collaboration between the researchers and the participants as end users of the material created more humane and child-friendly courseware (Balakrishnan and Claiborne, 2017; Danley and Ellison, 1999).

6.2.3. Improvement of the GUI. Asked about the GUI, the children were generally satisfied with the layout of the video, reading texts and navigational buttons. Only a few suggested making the font size bigger and changing to a lighter background. Perhaps this was because the children were accustomed to customizing their gadgets into dark or light backgrounds. However, this is a limitation of the courseware. It has only one default lighting background that is not adjustable.

What was noticeable in the pilot testing was that students did not perform well when doing longer reading exercises that required scrolling down the page. Student E said, 'Scrolling down to read more information is not helpful.'

When asked about this action, many claimed that scrolling was too inconvenient for them. Student F shared, 'I didn't know there were more items to answer. I thought it was only five. I didn't scroll down.' Student G explained, 'It is more practical for me to read and answer exercises that are shown in one screen only, like a true-or-false test.'

This experience of scrolling is a common issue in multimedia design (Støle et al., 2020) and is a limitation of the courseware's interface and setting. It does not offer links for students to access on the internet. This means that all reading texts are contained on the screen, which requires scrolling up and down. However, these comments from the children allowed the teachers to reflect on and to revise their choices in the multiple choice section without sacrificing the required competencies of the lessons.

6.2.4. Students' qualitative evaluation of IMMC in the implementation stage. After the collaboration and revision, the courseware was implemented in a Grade 8 English class of 39 students in a state university high school in Cebu, Philippines. The courseware was used as the primary instructional material for learning specific English-language competencies

Table 2. Students' qualitative evaluation of the IMMC.

ESD theme	*N* (%)	Code	Sample student response
Environmental conservation and protection	39 (100)	G4	I can only say one thing, always remember the three Rs. This would serve as a steppingstone to prevent global warming, where we will suffer in the future if it is not prevented. Global warming is the phenomenon where there is so much heat stored in the atmosphere, which would probably result in severe droughts on land, heatstroke of living things and more heat everywhere.
		G3	The videos and articles depict that global warming is taking place these days. It showed that fumes, factories and CFCs [chlorofluorocarbons] are the reasons why there is global warming.
Sustainable production and consumption	39 (100)	G1	Calamities and devastation are one. When crops are destroyed because of these, there is less production of crops and the demand gets higher. Prices will go up and less food will be eaten because of the high prices. As a result, there will be malnutrition, and sickness will follow. To fight food insecurity, there were investments done in order for crops to be produced well. I learned how to value food and value its importance.
		G21	I've learned that there are programmes that provide secure food. The WFP, or the World Food Programmme, provides food for the people to lessen malnutrition and to get them the right amount of food with proper nutrition.
Health promotion	39 (100)	G2	I've learned that the environment can really affect the people's health. If the environment is clean, the people . . . are ensured safe and humane homes. But if not, people are most likely to suffer from communicable diseases and illnesses, just like the people in dumping areas. People also suffer from the effects of the nuclear fall-out in Chernobyl, Ukraine. Children suffered because they were born with deficiencies.
		G20	I've learned how to take care of ourselves when we get sick. Drink plenty of fluids. Eat the right amount of food and, of course, get proper sleep and rest in order to recover. I've also learned that when we get sick, it's not good to depend on tablets always. It is better to use herbs and other plants with medicinal benefits to get well.

for one month. The teacher served as the facilitator of learning while the students were using the courseware on their individual computers in school.

An open-ended questionnaire and focus-group discussion were conducted with the students to determine their experiences of using the courseware. The findings show that the courseware promoted the seven ESD themes of environmental conservation and protection, sustainable production and consumption, health promotion, overcoming poverty, gender equality, cultural diversity and intercultural understanding and peace. Table 2 shows sample statements taken from the questionnaire.

Table 2 shows that the children claimed that the courseware promoted ESD and science concepts. Student G4 shared that global warming was caused by fumes and CFCs, while G3 added that global warming is a phenomenon in which there is too much heat in the atmosphere. G4 suggested doing the three Rs – reduce, reuse, and recycle – to prevent global warming.

For sustainable production and consumption, student G1 shared that when crops are destroyed by calamities, their supply and demand are affected. G21 added that the World Food Programme provides proper nutrition to fight malnutrition. G2 discussed the relationship between a clean environment and people's health. G20 advised that we should not be too dependent on using drugs to treat sickness but should instead use herbs and other medicinal plants.

The reflections prove the importance of conducting PAR among children before implementing the curriculum and instructional materials with them. The end users did not complain about experiencing difficulty in comprehending the reading materials on global warming and CFCs because these texts had undergone readability testing and revisions during the pilot testing. They were revised based on their reading level and were shortened, as recommended by the children. The whole experience of ease of reading supports the assertion of Zhao et al. (2017) that listening to the critical opinions of children as collaborators can promote the development of learner-centred material.

The children's active critiques in the pilot testing made the courseware's topics on sustainability and science more appropriate to their cognitive level and sociocultural needs (Macdonald, 2012). Thus, the ESD and science topics, which were deemed to be complex and ambiguous (Kioupi and Voulvoulis, 2019), gained acceptability among the student end users. This is validated in the reflection of student G3: 'The courseware showed that fumes, factories and CFCs are one of the reasons why there is global warming because of the greenhouse gas that is produced.'

The students' positive evaluation proved that the use of IMMC in teaching sustainability among younger students is beneficial. The data confirmed some studies that found that the use of innovative and interactive digital pedagogies with inquiry can contribute to successful ESD contributions (see e.g. Cebrián et al., 2020; Ricard et al., 2020). The interactive feature of the IMMC aroused the interest of the students to learn these technical concepts (Zeti et al., 2020).

When educational digital materials use sound interface design, content and activities, they have the potential to improve the learning process (Zeti et al., 2020). IMMC can be an effective strategy in stimulating students' interest in learning vocabulary related to science or ESD concepts (Yue, 2017).

It is therefore feasible to use CBI in English-language teaching. The Grade 8 students learned not only language skills but also ESD and science topics, which are required in the curriculum. These science concepts prepared the students in their academic reading in their biology and social sciences classes. This research shows that CBI can promote multiliteracy through learning language content, science and technology (Snow, 1998; Stoller, 2004).

7. Conclusion

We can draw the following conclusions and make the following recommendations on using PAR with children as collaborators in developing science- and ESD-based IMMC.

CBI promotes an interdisciplinary approach in developing IMMC because it develops a dual commitment to the learning of English language and the learning of science- and ESD-based concepts. The IMMC content does not only focus on the superficial structures of language but also empowers the users to critically reflect on sustainability issues and perform sustainable actions. The integration of sustainability in the IMMC before, during and after the lessons promotes explicit instruction on the obligatory science content. The contents become the springboard and motivation for review lessons for language instruction. They become the topic in discussing English-language competencies and grammar and the theme for written assessments or quizzes. The IMMC aims to develop communicators with scientific knowledge of sustainability and a willingness to take greater responsibility for creating a sustainable world.

The use of PAR with children improved the IMMC's GUI, delivery of instruction, choice of topics, the length of written texts and videos, and the number of exercises. The collaboration with children in the pilot testing and implementation stage allowed us to customize the IMMC based on the children's preferred learning context without sacrificing the mandated learning competencies. The children suggested that the entirety of the reading texts and quizzes must be seen completely at the first glance. They added that scrolling a cursor up and down with a mouse was inconvenient and might make them miss other items. On the question of jargon or technical vocabulary related to science and ESD concepts, the children suggested that we explain the meaning of such terms before they read or view the selection in order to buttress their reading or viewing comprehension.

We recommend that language curriculum and instructional material developers use CBI as an interdisciplinary approach in developing contextualized digital materials. They can conduct a needs assessment with their students to determine the choice of topics or themes on which they can anchor their students' language competencies. In addition, they can use PAR and collaborate with their students on academic topics or interesting social issues that can be used as a springboard for the lessons and assessments.

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Building scientific capacity in disaster risk reduction for sustainable development

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Abstract

As climate warming intensifies, the frequency and intensity of disasters are also increasing, posing challenges to global sustainable development. The concept of disaster risk reduction (DRR) provides strong impetus for reducing disaster risk and vulnerabilities by employing the scientific and technological developments of recent decades. However, there is a need to enhance the capacities of different communities to use emerging digital infrastructure, not only in promoting DRR but also in ensuring sustainable future development. Limited access to and availability of data are restricting comprehensive understanding of these challenges. In many countries, the key areas for capacity development include collecting information from alternative and emerging data sources and meaningfully integrating it with data from traditional sources. Software and data analysis are becoming widely accessible due to open-source initiatives, while cloud computing technologies and programmes such as CASEarth provide valuable resources for multisource data integration, contributing to information-driven policy and decision-support systems for DRR.

Keywords

Big Earth data, disaster risk reduction, scientific capacity development

1. Introduction

The industrial revolution of the 20th century and the ongoing technological revolution have brought rapid, positive transformations in many societies and economies. The developments of this continuing process of modernization have been largely characterized by economic development and directed towards improving livelihoods to facilitate social progression (Guo et al., 2020). However, this impulsive drive towards development has produced counterproductive influences on our environment and, consequently, our own well-being, and increased our vulnerability to a large number of risks, including risks of disasters. Over time, the costs of these transitions and transformations are becoming increasingly evident, as are the complexities of mitigating these costs.

Historically, public policy in disaster research has concentrated on responding to disasters, so national disaster management plans have directed most of their funding towards response and

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recovery, ignoring the mitigation and preparedness stages of the disaster management cycle (McBean and Rodgers, 2010). Response and recovery may be aided through disaster assistance and relief in the form of international humanitarian aid and the work of volunteers from different countries and international organizations to provide respite to communities at the local level and help support rehabilitation and recovery efforts. However, these financial, material and human resources are neither unlimited nor available indefinitely. Post-disaster relief efforts are generally event-specific and not designed for long-term resilience of affected areas (Birkmann and Von Teichman, 2010). Moreover, as observed during the global COVID-19 pandemic, the capacity to provide assistance to other countries and communities is considerably constrained as the scale of a disaster increases.

From accumulated experiences of the destruction caused by unprecedented natural events, together with lessons from poor decision-making, it is now understood that, while the severity of disasters may be beyond human control, the associated risks and vulnerabilities can be managed, mitigated or reduced, giving rise to the concept of disaster risk reduction (DRR) (UN Office for Disaster Risk Reduction [UNISDR], 2015), which is focused on reducing the vulnerability and exposure of people most at risk. It has also been established that the rate of return on investment in DRR is between four and seven times (United Nations Economic and Social Commission for Asia and the Pacific [UNESCAP], 2017). Mitigating risks and exposure is increasingly becoming unavoidable, as both population increases and the changing climate are considerably complicating risk and exposure scenarios. The growth of urban populations, driven by the pursuit of better economic opportunities, has forced people to live, by choice or circumstance, in more hazardous zones. This has also increased the risk of natural hazards and raised the numbers of people and communities exposed, particularly in geographically vulnerable locations (McBean and Rodgers, 2010).

DRR is a multidimensional, multiscale, cross-cutting issue that requires input from not only the natural sciences but also the social sciences and the involvement of numerous stakeholders. In particular, with the recent drastic and sudden changes in climate (attributed to enhanced global warming), the resulting dynamic outcomes are too complex and variable to comprehend without a systematic understanding of the risks and likely consequences of ongoing developmental practices, entailing natural, socio-economic, health and engineering problems. Unfortunately, even with a consistent international focus and awareness-raising on disaster-related events worldwide, problems in implementing DRR measures persist. Rapidly developing technology and modern sciences provide new solutions to problems and new means of analysis, allowing the quantification of several aspects of disaster risk and providing opportunities to systematically study the risks and consequences of disasters. A science-to-policy approach is, therefore, needed to facilitate our understanding of the convoluted mortal and economic vulnerabilities of populations and their interests at various spatial scales. In a more connected world, policy inconsistencies resulting from administrative demarcations can be amicably reduced for shared resources, vulnerabilities and other DRR challenges through intelligible scientific evidence. Such evidence also provides opportunities to create consensus on politically sensitive issues (Carabine, 2015). However, both scientific capacity and the capacity to implement science-based solutions and policies are rather limited in many parts of the world.

2. Science, technology and innovation in the Sendai Framework and 2030 Agenda

The Sendai Framework for Disaster Risk Reduction, building on the experiences of the preceding Hyogo Framework for Action, has the single goal of strengthening resilience through two courses of action: (1) reducing risk, by lowering hazard exposure and vulnerability to disasters; and (2) increasing preparedness for response and recovery.

The goal also defines several measures, which can be divided into three domains: (1) the science domain, defined by structural, health, environmental and technological measures; (2) the governance domain, defined by economics and legal, political and institutional measures; and (3) the public domain, comprising social, cultural and educational measures.

However, the three domains are interdependent: actions in one can overlap with actions in another, and cooperation and coordination are needed to facilitate, enable and achieve various measures. For example, the science and governance domains have strong feedback loops, while the public domain depends strongly on both of them. The Sendai Framework also identifies four key priorities: understanding disaster risk, strengthening DRR governance, investing in DRR, and responding effectively and 'building back better'.

The DRR concept is also integral to sustainable development (Birkmann and Von Teichman, 2010); hence, DRR is embedded in the United Nations (UN) 2030 Agenda for Sustainable Development, and the Sustainable Development Goals (SDGs) have several intersections with the Sendai Framework. Examples in SDGs directly related to DRR include Target 1.5 (reduce exposure and vulnerability), Target 2.4 (improve adaptation), Target 3.d (risk reduction and management), Target 9.1 (sustainable and resilient infrastructure), Target 11.5 (reduce death, affected people and economic losses from disasters), Target 11.b (resilience to disasters), Target 13.1 (resilience to disasters), Target 13.3 (early warning systems) and Target 15.3 (prevent land-degradation and associated hazards). There are also several more targets that indirectly require improvement in DRR capacity.

Improved scientific capabilities and knowledge have enabled the role of science in several aspects of DRR. Accordingly, the Sendai Framework (unlike the Hyogo Framework for Action) clearly establishes roles for science and technology, including cultural, social, economic and natural scientists working together as a distinct (collective) stakeholder in developing a comprehensive DDR strategy (Calkins, 2015).

The UN Office for Disaster Risk Reduction (UNISDR (2016), which became UNDRR on 1 May 2019) released 'The science and technology road map to support the implementation of the Sendai Framework for Disaster Risk Reduction' (see also Dickinson et al., 2016), which was subsequently revised in 2019 (UNDRR, 2019b). The road map comprehensively lists 51 actions for all four Sendai Framework priorities. These actions are intended to promote the achievement of four outcomes: improving the current state of knowledge; promptly disseminating actionable knowledge to relevant users; quantitatively monitoring progress towards DRR; and improving decision-making capacity at various levels. The road map does not recommend a particular order of actions but offers detailed guidance towards inclusive, accessible and multidisciplinary science.

The 2030 Agenda also recognizes the importance of science and technology, particularly by identifying science, technology and innovation (STI) as a key tool for implementation. The UN has also formalized the Technology Facilitation Mechanism, which was launched in September 2015 in accordance with the Addis Ababa Action Agenda. It is designed to enhance STI through multistakeholder collaboration to achieve the SDGs, with the aim of enhancing international cooperation to improve access to and sharing of technology and knowledge for sustainable development (Walsh et al., 2020).

The mechanism has three main elements: (1) a UN Inter-agency Task Team (IATT), facilitated by a 10-member group of representatives from different backgrounds, including civil society, the private sector and the scientific community; (2) a multistakeholder forum on STI for the SDGs (the STI Forum), to discuss, facilitate and support coordination and collaboration; and (3) an online platform for information on existing STI initiatives, mechanisms and programmes.

The online platform is an initiative of the UN Department of Economic and Social Affairs and the UN Office of Information and Communications Technology; it is likely to provide much-needed guidance through consolidating information on existing efforts and to help promote open and accessible exchanges of ideas and the transfer of knowledge and experiences. This online platform was launched on 15 July during the 2020 High-Level Political Forum and is currently enlisting several partners in four primary categories: publication and knowledge resources; technology solutions; financial resources and matchmaking; and capacity development and miscellaneous.

The IATT (2020) contends that the achievement of the SDGs can be facilitated and accelerated through STI and advocates urgently leveraging the potential of STI for this purpose. This is especially important because no country is currently on course to achieve the SDGs by the 2030 deadline (Walsh et al., 2020). The IATT proposes the development of STI for SDG road maps and action plans at different levels, including subnational, national and global levels, as the required information, knowledge and experience are scattered and efforts with potential to support STI are fragmented across different administrative scales (IATT, 2018). The IATT also encourages the incorporation of the various road maps into existing planning and implementation documents to avoid duplication and waste of effort and resources. In 2020, the IATT's guidebook identified several challenges for developing countries, such as the capability to absorb, deploy and use several current technologies within existing technological infrastructures. Accordingly, the guidebook stresses the need to reassess the SDG trajectory in the light of recent progress and improved awareness about the opportunities and risks of science and technology. It also calls for leveraging digital technological transformation, emerging practices and lessons learned to formulate new and innovative solutions.

3. Scientific capacity development for DRR

With the increasing frequency and intensity of disasters, local capacities for managing hazard conditions and disaster exposure and vulnerability – founded on sound and verifiable scientific practices – are essential. Scientific capacity is, therefore, needed to innovate and develop viable solutions and also to aid the adaptation of ideas and innovations to local conditions and realities. Unfortunately, scientific capabilities, resources and expertise are unevenly distributed around the world, such that many communities struggle to incorporate scientific methods in developing DRR strategies. This is strongly reflected in Elsevier's (2017) report titled 'A global outlook on disaster science: from 2012 to 2016', disaster-related research output disproportionately emanated from countries that are already prolific in scholarly output, while emerging countries–which are vulnerable to a large variety of disaster risks – generated relatively little research output. More concerning is that the countries with higher disaster mortality have low disaster research output, while countries with higher economic costs tend to have higher disaster research output.

This lack of scientific capacity is well understood in several other fields, and efforts to develop scientific capacity and technology transfer have been ongoing, entailing flows of knowledge, resources, technology and expertise from developed to developing nations (Harris, 2004). However, this process is often difficult to implement operationally, so it is critically important to understand the purpose of the capacity-development exercise (Missika, 2006). Traditional capacity-development efforts aim to improve access to education, training, funding, information, equipment and supplies; however, these resources often go underutilized due to a lack of organization, organizational structure or institutions (Missika, 2006) to enable systematic and objective work towards predefined targets and goals.

However, from a disaster-risk perspective, other capacity aspects beyond organizational and structural improvements must also be considered, such as linking climate change adaptation to DRR (Birkmann and Von Teichman, 2010; McBean and Rodgers, 2010). It is quite evident from disasters between 2000 and 2019 that both the number of disasters and their adverse consequences for lives and economies have increased considerably. In particular, the number and impacts of climate-related disasters have risen significantly, compared to those of other forms of disaster. The rate of climate-related disasters (floods, storms and droughts) accumulated to about 77% in the past two decades. Globally, although earthquakes are the deadliest disaster type, floods, droughts and storms collectively account for approximately 94% of the total number of people affected by disasters (UNDRR, 2019a). This strongly suggests that climate change and environmental degradation are linked to the rising frequency and intensity of disasters. Therefore, a well-designed DRR management plan should incorporate well-designed climate change adaptation and environmental management components to simultaneously address these multidimensional aspects.

However, DRR management plans are generally designed using historical data on risk and vulnerabilities that may change over time and under the influence of dynamic factors such as climate change, which are not regularly revised but revisited only after a disaster (Prabhakar et al., 2009). Moreover, risk assessment and modelling are often designed to detect risks that have been recognized, ignoring small but recurrent events that are equally damaging when aggregated (UNDRR, 2019a). Furthermore, since disaster vulnerability and exposure scenarios are largely unique to particular communities, DRR capabilities need to be inclusive of different forms of knowledge and enable the integration of actions at different scales (Gaillard and Mercer, 2013). This complexity in DRR requires large volumes of data, so a better balance of natural and social data in addition to local and scientific knowledge is required, and that data must be openly accessible to different stakeholders, including the affected people (Birkmann and Von Teichman, 2010). In tackling the growing challenges of disasters, integrated multidisciplinary science provides the means to develop approaches across geographical regions and addressing multiple hazards. However, scientific understanding and solutions remain neglected due to a lack of focus on generating policy-specific information that can be understood by a large variety of stakeholders and end users to enable social interventions designed to reduce risks. Therefore, there is a strong need to develop scientific capacity to translate DRR-related information to enable progress towards a science–technology–policy framework.

4. Lack of data is limiting scientific capacity

Data is quickly becoming the resource that fuels most modern digital infrastructure. However, it is largely directed towards e-commerce applications in the private sector, particularly by the services industries. While governments, particularly in developing countries, are adept in traditional data-collection methods, they have access only to limited data sources, and their data-collection mechanisms are non-periodic and inefficient. Furthermore, most African countries are unable to generate consistent, accurate and reliable data due to high costs, scattered populations and security implications, creating substantial gaps in the data needed to support policy- and decision-making (Kganyago and Mhangara, 2019); other small and developing nations face the same challenges. Consequently, the public sector in these countries is data-constrained in numerous national activities, including evaluating and monitoring DRR and the SDGs. Disaster loss data is not well maintained in many developing countries (Rautela, 2016), and the UNDRR (2019a) reports significant data gaps on disaster-related impacts and economic losses, particularly in African countries. These deficiencies are likely to be due to developmental costs and/or lack of appropriate methodologies to forecast societal development at the meso- and micro-scales, which is important for understanding changing vulnerabilities (Birkmann and Von Teichman, 2010). For scientific data, the lack of technical, financial and human resources and capabilities also contributes to the problem of non-continuous spatial and temporal data coverage.

In many developing countries, disaster science is responsive to disaster events (Elsevier, 2017), so the limited coverage and availability of data both impede comprehensive efforts to develop and apply DRR strategies. The lack of data is compounded by restricted access to available data under the policies of national administrations at various levels, aid and relief organizations, NGOs and the private sector. Reasons for access restrictions include lack of communication, low interest and simply the absence of incentives. All these factors result in the creation of data silos, which reduce the scope of information available to inform decision-making. This also causes a disconnect between bottom-up approaches to DRR, which focus on practice, and the top-down approaches, which focus on policy (Antofie et al., 2017). The lack of data (especially essential social and economic census data) further exacerbates this divide, particularly in geographical areas with dynamic fluctuations of population and economic instability.

Access to relevant data and capabilities to assess that data are crucial for identifying developmental priorities and developing baselines against which to measure a country's current status, enabling the identification of the correct course for developing SDG road maps and action plans (IATT, 2020). The UN and other international organizations, such as the World Bank, have undertaken several efforts to improve the data collection, data analysis and general statistical capacity of developing nations, including the Marrakesh Action Plan (Ngo, 2015) and the updated Busan Action Plan for Statistics (Organisation for Economic Co-operation and Development [OECD], 2011).

More recently, the Cape Town Action Plan for Sustainable Development Data (HLG-PCCB, 2017) identified six strategic areas for action: coordination and strategic leadership, innovation and modernization of national statistics, strengthening strategic activities and programmes, dissemination and use of data, multistakeholder partnerships, and resource mobilization and statistical-capacity development.

Data is critical to improving scientific capacity because it helps to improve in-depth understanding of disasters and associated risks, assisting decision-makers to identify and prioritize new and more adapted measures to counter disaster challenges (UNDRR, 2019a). In particular, for risks shared between communities, accessibility to data is critical for a comprehensive and collective response. Open access to data and information is, therefore, vital to addressing shared risks and challenges. Hence, it is necessary to improve the generation of evidence and to strengthen the multidisciplinary, multistakeholder, interorganizational and intergovernmental processes for DRR (Carabine, 2015).

5. Earth observation data for DRR

Whereas social data is riddled with gaps, space-based Earth observation platforms have provided invaluable synoptic and periodic data coverage over the years. Indeed, the large volumes of Earth observation data collected over the years and its integration with other spatially referenced data – enabled by improved data storage and processing capabilities – provide effective means of understanding complex multiscale and multidimensional processes and facilitate decision-making (Gulgun et al., 2009; Liang et al., 2021). Improving the spatial and temporal resolution of Earth observation data will allow the adoption of large-scale operations at local scales (Guo et al., 2018). In the past two decades, significant improvements have been made through active investments in Earth observation systems, sensors and platforms (Guo et al., 2018) to improve the viability of data using advanced algorithms and data-processing methodologies, enabling the quantification of different surface and atmospheric parameters (Guo, 2017a, 2017b).

Earth observation data has extensive applications in disaster management and multiple uses in different stages of the disaster management cycle (Le Cozannet et al., 2020), particularly in coordinating emergency responses after an event (Voigt et al., 2016) for rapid response and recovery (Lorenzo-Alonso et al., 2018).

Similarly, Earth observation data can be used to: provide logistical information for post-disaster reconstruction and rehabilitation; estimate hazard impacts and provide relevant information on risk of and exposure to disasters (Ehrlich et al., 2018); operate early-warning and monitoring systems (De Guenni et al., 2005; Van Westen, 2013); and facilitate forecasting, risk modelling and aid in recovery-related activities following disasters (Leibrand et al., 2019).

In an urbanizing world, rapidly expanding and changing urban settlements can be monitored easily using Earth observation to estimate vulnerability and risks (Chen et al., 2019). This can also help in planning for the resilience of critical infrastructure and social services by providing relevant and actionable information (Leibrand et al., 2019).

DRR science is constantly evolving with advances in Earth observation data. New and improved datasets and improvements in data-analysis techniques, the capacity to extract valuable information and the degree of geographical detail continuously advance DRR. Various aspects and disciplines of DRR science have extracted numerous benefits from developments in Earth observation technology and methods. For example, the approach to large-scale floods at each stage of the disaster management cycle has benefited greatly from Earth observation data, through improving numerical weather predictions, addressing data gaps and detecting surface water extent and heights (Alfieri et al., 2018).

Similarly, several drought indices have been developed using Earth observation data (Aitekeyeva et al., 2020), while fire-risk estimation has made extensive use of spatial and temporal Earth observation data, including by deriving information on meteorological parameters and developing new techniques to detect burned areas (Shan et al., 2017) and active fires (Lin et al., 2017, 2018, 2019). Earth observation data has also been used to develop proxies for monitoring aspects of built-up, economic, social and natural environments in urban settlements to inform disaster risk management (Ghaffarian et al., 2018).

Potential uses of Earth observation data for DRR are constantly being explored, and the development of innovative solutions has been aided by improving technology and new Earth observation systems. New satellite constellations are being developed to improve both the spatial and the temporal resolution of data, and thereby provide increasingly useful risk information. Examples include the Sentinel satellites, the COSMO-SkyMed constellation (Kwak, 2017) and the Environmental Protection and Disaster Monitoring Constellation (Guo et al., 2018). Argentina is also planning to launch SAOCOM 1B to join SAOCOM 1A and work with COSMO-SkyMed to complete the Italian-Argentine Satellite System for Emergency Management (De Ambrosio, 2020). An increasing number of governments are looking to develop in this sector. Several African nations – including Nigeria, Egypt, Algeria, Kenya, South Africa and Gabon – have established national space agencies and, in some cases, also launched Earth observation satellites (Kganyago and Mhangara, 2019).

However, there are particular developmental hurdles. Countries that have developed space-based Earth observation capabilities have had to invest extensive financial capital over several years, developing human resources and physical infrastructure in the process, but a range of limiting factors prevent many nations from pursuing the same strategy. Also, the transfer of satellite and sensor technology is a complicated state-level policy issue.

Nevertheless, data sharing is increasingly being pursued in the light of rising transboundary problems, such as global warming and the intensification of disasters, and the relevance of Earth observation data to various applications in this field makes that data ever more important. Earth observation data is especially relevant in areas lacking formal arrangements for ground-level observations, due to lack of accessibility or capacity among many other factors. Where ground-level observation data is available, Earth observation data provides complementary spatial information. Earth observation data can also help to overcome the limitations of several traditional survey methods (Kganyago and Mhangara, 2019).

Recognizing these benefits, the international community has begun to increase the volume of freely available Earth observation data, easily accessible over the internet, over the past two decades. The US Geological Survey, the National Aeronautical and Space Administration, the European Space Agency, the Japan Aerospace Exploration Agency, the National Institute for Space Research and many other organizations have large repositories of data online, while several free and open-source software packages and applications for using and analysing Earth observation datasets are already widely employed in research by the spatial data community. For immediate disaster relief, the International Working Group on Satellite-Based Emergency Mapping helps to coordinate mapping efforts for international responses to disaster events, facilitating several aspects of disaster response (IWG-SEM, 2018).

Unfortunately, Earth observation data is still underutilized for other stages of the disaster management cycle, such as vulnerability and exposure mapping (Le Cozannet et al., 2020). In developing countries, such as in Africa, the overall research output using Earth observation data is limited (Kganyago and Mhangara, 2019), which is likely to be a consequence of low internet connectivity, insufficient bandwidth for downloading the data and the poor availability of hardware able to process and analyse it. With improving digital infrastructure, such as the introduction of 5G networks and the essential processing power provided by cloud computing, the use and analysis of Earth observation data are becoming increasingly viable. Cloud computing platforms provide key capabilities for developing and disseminating products and services related to several disciplines, including DRR, and help to resolve several of the capacity and data issues in many countries (Kganyago and Mhangara, 2019).

6. The concept of Big Earth Data: Multisource data integration

The rapid development of computers and of information and communication technology (ICT) has allowed increased interconnectivity and exchanges of data and information. Across the world, digital infrastructure is being prioritized and connectivity is improving. For instance, the numbers of fixed broadband users and internet users have risen in both Asia and Africa, especially in the past 7 or 8 years. The African Union (AU) is developing the Digital Transformation Strategy supported by the World Bank Group, AU member states and other partners to build the foundations for a digital economy, which involves establishing digital infrastructure and platforms, enhancing digital skills and introducing or improving digital financial services and entrepreneurship (IATT, 2020). More broadly, Africa, Asia and Oceania all have high growth potential and are adopting new broadband technologies (Broadband Commission for Sustainable Development [BCSD], 2018). In terms of infrastructure, the least-developed nations have lagged behind considerably, but it is expected that broadband internet user penetration will reach 35% by 2025 (BCSD, 2018), potentially accompanied by rising demand for and utility of online data analytical services.

In developed countries, interconnectivity has moved beyond the social realm into the virtual with the realisation of the internet of things (IoT), allowing the development of smart platforms. This has only been possible due to the vast amounts of data generated by human interactions with modern applications and technologies. These large datasets, commonly termed 'big data', have proven to be beneficial for businesses, resulting in data becoming a commodity and strategic resource in the modern world. Extensive investments and efforts are being devoted towards rapidly developing capability, capacity and infrastructure for handling big data, leading to the development of a new scientific discipline: big data science. This new discipline normally deals with four aspects of data: volume (referring to the quantity of data), velocity (referring to the speed of data generation and processing), variety (referring to the types of data) and veracity (referring to the availability and accountability of data) (Acharjya and Ahmed, 2016). Big data science and advances in artificial intelligence (AI) and machine learning are providing important opportunities for data analysis and automation (International Institute for Sustainable Development [IISD], 2018). With the rapid adoption of emerging technologies, AI and data-driven processes in all aspects of the social and economic domains, different disciplines are exploring their viability to support innovative solutions to challenges. New big-data-driven applications are fuelling platforms that employ learning-based analytics to generate valuable information and are enabling smart systems and technologies (Guo et al., 2020).

The UN has established the Global Working Group on Big Data for Official Statistics. On behalf of the working group, and in collaboration with the World Bank, the UN Statistics Division maintains an inventory cataloguing big data projects of relevance to official statistics, SDG indicators and other statistics needed for decision-making on public policies, as well as for the management and monitoring of public sector programmes and projects. The inventory summarizes innovative applications of big data in a large variety of use cases. However, a large number of projects listed are using huge volumes of data generated from ICT and the IoT; as such, their potential applications are limited to measuring social aspects and, given the availability of services, largely centred on urban areas, especially in developing regions. The inventory also includes projects applying very innovative techniques for geospatial applications, but very few focus on disaster management. There are likely to be many active projects not yet listed in the inventory. However, the projects currently listed can be regarded as representing the trend towards big-data-based research in support of global initiatives.

For a comprehensive understanding of disasters in the context of developmental and climatic changes, and to improve the current state of knowledge and monitoring of DRR progress, both domain-specific and multidisciplinary research are required.

This needs to be driven by constant streams of reliable and verifiable data, enabling the timely dissemination of actionable knowledge to relevant users through platforms and structures that provide relevant information, translate scientific knowledge into terms more adaptable for DRR policy and management, or both (Albris et al., 2020). Such platforms will help to consolidate the efforts of the Earth observation community in different domains, including the supply of disaster risk applications with better standardization of Earth observation products and services to facilitate risk assessments and enable credible and actionable information that is accessible and understandable (Lorenzo-Alonso et al., 2018).

As data sources have diversified, data integration has become an attractive and active space for innovation. The concept of integrating multisource data for earth science has been termed 'Big Earth Data' (Guo, 2017a); it calls for the use of both traditional methods (including statistics, mathematics, computer science, remote sensing and geographic information systems) and more advanced methods (data mining, machine learning and AI) to analyse complex and interconnected relationships. With ease of access to data and services to convert that data into information, the Big Earth Data concept has relevance in DRR and important utility in future sustainable development policies and practices. However, compared to traditional big-data analysis, Big Earth Data presents additional challenges. First, temporal and spatial scales complicate analyses of Earth observation data. Second, as multiple centres around the world develop Earth observation technology, the necessary sources and standards of data for a particular analysis are diversifying. The need to overlap different sources of data at varying scales is presenting data-interoperability challenges. Therefore, to improve the interoperability of Big Earth Data, it is necessary to establish unified standard formats, units and conversion algorithms. In the past 2 years, multiple efforts have begun to introduce, promote and facilitate the adoption of these modern emerging practices to create innovative solutions for disaster risk management and sustainable development (for details of promising examples, see Guo, 2019).

7. The CASEarth programme: Towards a Big Earth Data approach for the SDGs

In developing countries, the lack of infrastructure for processing, analysing and storing large volumes of Earth observation data, together with limited technical capability and awareness, results in the underutilization of free satellite data and analysis software (Kganyago and Mhangara, 2019). Several online services developed by different organizations are already providing access to specialized data and data-analysis facilities. Increasing accessibility due to enhanced digital infrastructure is also improving access to these resources. These developments are helping to overcome the limitations of data-processing power and data-storage capacity that complicate the use of large, integrated datasets. With the growing number and rising availability of data centres and cloud analysis services, the limitations on analysing large volumes of data and the requirement for capable hardware to process that data have been considerably reduced.

To facilitate the development of universally accessible online resources, and to provide the capability for data-intensive research on global problems, the Chinese Academy of Sciences launched the Big Earth Data Science Engineering (CASEarth) project as part of the Strategic Priority Research Programme (Guo, 2017b). CASEarth is designed to combine technical problem solving, team building and platform building. Broadly, the project is set to establish the International Research Centre of Big Data for Sustainable Development Goals, as announced by Chinese President Xi Jinping during his address to the UN's 75th General Assembly session on 22 September 2020. CASEarth consists of several key projects designed around the themes of technological innovation, scientific discovery, macro-decision-making and knowledge dissemination.

The CASEarth project plans to launch China's first earth science satellite in 2021, to provide Earth observation data with several potential applications in sustainability and DRR (Guo et al., 2020). The big data and cloud service platform of CASEarth is helping to overcome bottlenecks in data access and sharing (Guo, 2017b). The platform will provide access to a diverse range of capabilities for integrating data from multiple sources and at multiple scales, which could be analysed using established algorithms and tested methodologies. CASEarth is also developing a decision-support system to facilitate transforming data into actionable information through a wide variety of scientific resources, the availability of which spares users the time and cost of developing extensive infrastructure and accessing expensive equipment.

These efforts are motivated by the need to link policy with science and to develop avenues to promote the adoption of scientific methods for policy development and decision support. For this purpose, CASEarth is working to develop case studies, model research and reference materials to encourage young talent, researchers and policymakers to use emerging technologies and data science methodologies to develop innovative solutions to challenges and national strategies for sustainable development, both within and beyond China. CASEarth has also prepared a series of reports titled *Big Earth Data in Support of the Sustainable Development Goals*, presented as part of the Chinese Government's submissions to the UN's 74th and 75th General Assembly sessions.

Several similar online services, which provide access to and the ability to analyse remote sensing and other forms of geospatial data from different sources, are in the early stages of development and are still expanding their user bases. They are designed to provide necessary computation power and access to large quantities of Earth observation data, along with tools to analyse and visualize that data. Making rapid progress and showing significant potential, these services provide a good direction for developing human capacity for future research and a foundation for promoting data sharing and integration. The facilities also give developing countries alternative channels to pursue science and considerably reduce their infrastructure investments, allowing them to prioritize investments in developing capacity and human resources. This will provide a strong and well-educated foundation for their future development in science and technology.

8. The way forward

DRR is a complex undertaking and requires an understanding of diverse multiscale processes that interlink and influence one another. A comprehensive assessment of disaster risks and challenges requires periodic information on changes in vulnerability and risk over temporal and spatial scales, in addition to information on variations in countries' level of development, as developed nations are prone to economic risks while developing nations more typically face high mortality rates (Elsevier, 2017; UNDRR, 2019a). Therefore, the DRR community must simultaneously address a wide variety of complex socio-economic and socio-environmental challenges. The community's efforts aim to strengthen the science–policy interface by facilitating understanding of the complicated interconnections between climate change, sustainable development and disasters, leading to meaningful and sustainable actions towards DRR.

Traditional methods and data sources are inadequate and cannot completely represent these complex relationships. Therefore, in addition to improving data collection using traditional methods, alternative and emerging data sources and methods are being developed to enhance the role of scientific and verifiable approaches in promoting viable and sustainable policies and decision-support systems. To facilitate these developments in DRR, national governments must first move from management-oriented policy to information-based policy and decision systems. This simple but critical shift will help to organize the flow of information and develop the integration of top-down and bottom-up channels, providing complementary experience and insights as the foundation for better decision-making systems. Developing countries should focus initially on national data-collection systems. They should ensure that essential development projects develop domain-specific data-collection mechanisms: for example, a project focused on agriculture or infrastructure development should establish mechanisms for collecting periodic data on various relevant indicators for the SDGs and DRR within the target area or community.

Data analysis is becoming widely accessible due to increased connectivity and open-source initiatives. AI algorithms and machine-learning techniques provide the tools to make sense of complex scenarios, along with data-analysis techniques and methods that can be easily transferred from one place to another and communicated or disseminated through training and resource-development exercises. As in other disciplines, collaborations and human-resource-development activities can rapidly facilitate capacity enhancement within developing countries, enabling the use of these advanced techniques in DRR. However, they are data-demanding approaches, and comprehensive, integrated data analysis is especially limited by the lack of available data.

An important early step is to identify the data gaps within the knowledge- and information-management platforms that inform DRR policy. These gaps can be filled using both established and emerging data sources. Data from geospatial sources, particularly a large variety of remote-sensing platforms, is increasingly being made available, and, with the launching of multiple near-Earth orbit observation platforms, high-resolution datasets are likely to become more affordable. Over the past several years, the Earth observation community has made great efforts to improve Earth observation infrastructure, including its technology and the viability of data, for a large variety of applications, such as in DRR. Geospatial data is particularly suitable for filling the data gaps on environmental and geodynamic processes. The utility of that data will be enhanced and simplified through developments in online services, fuelled by improved cloud computing infrastructure, services and data products (Guo et al., 2020). Earth observation data and spatial data infrastructure will facilitate the linking of bottom-up and top-down approaches (Antofie et al., 2017).

However, for social processes, geographical and spatial data coverage is not always adequate, raising the need to find ways to integrate data from these different and emerging sources. Other sources of data using informal mechanisms, such as the emerging concept of citizen science, can be employed to fill the gaps. One excellent example is the formalized mechanism of participatory data collection established by the University of Namibia to aid data collection on informal settlements, the residents of which are largely vulnerable populations most exposed to disaster risks. This mechanism allows students to participate in data-collection exercises in collaboration with relevant authorities, NGOs and relief organizations. In addition to collecting valuable data, public participation in data collection raises awareness and mobilization, eventually improving public capacity for DRR.

One key challenge, however, is the integration of data from these multiple sources, including informal sources such as citizen science, telecommunications and social media. A standardization process is needed for data from these sources to be credibly incorporated in the information and data ecosystem as a complement to traditional and geospatial data. National statistical offices should develop policies to evaluate the strengths, weaknesses and limitations of these complementary sources and formalize a system to integrate them within the national data ecosystem. Proper training, data-collection protocols and standardizations can help to generate high-quality, reliable data for formal analysis and integration, even for data from non-traditional sources. Moreover, citizen science data and geospatial data can be used for cross-validating each other, which has already been demonstrated by Leibovici et al. (2017) to be useful through an automated quality-assurance workflow.

Furthermore, information from diverse sources and multiple platforms of local data, Earth observation data and big data need to be integrated in a meaningful and standardized manner to ensure credibility and acceptability. To facilitate this process of generating knowledge from integrated sources of information, there is a need for knowledge- and information-management platforms at the national and international levels, accessible to a large variety of users, to guide actions towards adopting dynamic vulnerability and adaptation strategies (Birkmann and Von Teichman, 2010). The CASEarth platform for Big Earth Data provides a good example of such a system.

Regarding the lack of accessibility, public and commercial institutions are typically reluctant to make data easily and readily accessible for non-commercial scientific research. To enable the development of national capacity geared towards better DRR policies, data-sharing practices need to be encouraged and facilitated. Knowledge and information platforms will particularly facilitate this process and also help to prevent duplication of efforts and wasted resources in re-collecting data that has already been gathered.

Broadly, there is a need to focus on capacity-development programmes for national data collection, databases and integration systems. These activities should be facilitated through multistakeholder cooperation at both the national and international levels. The STI Forum provides one prominent example of a platform to enhance international collaboration. At the international level, efforts are needed to bridge the digital divide (Guo, 2018), as data collection and analysis are becoming increasingly digital. If the digital divide is not reduced, it might increase the global data gaps that hinder the effective monitoring of sustainable development and overall global progress. For regional-scale challenges, international collaborative agreements can help to enhance information and data sharing. This requires increased facilitation of cooperation within the Global South and between the Global North and Global South.

9. Conclusion

DRR and the drive towards sustainable development require information-driven policy and decision-support systems due to the dynamic nature of climate change and the complexity of social and environmental interlinkages. There is a need to develop scientific capacity to establish and maintain these systems through investments in data collection and analysis infrastructure. Despite the large number of data-analysis services being made available online, particularly for geospatial data, there are still data-interoperability challenges to address. Multisource data integration and analysis infrastructure, such as the workable example developed by CASEarth, cannot be replicated immediately in developing countries, as such infrastructure requires large investments and strong technical capacity. However, for such online services, improving internet connectivity will ensure accessibility for developing nations, which can thus benefit from these technological developments, although there are still data gaps to address in these regions. A large number of geospatial data sources have been developed and made available and can help to fill these data gaps. Other non-conventional data sources should also be further explored, standardized and formalized to improve our understanding of both local and regionally shared challenges. Collaboration and data sharing also need attention from multiple stakeholders at the international level. The key aims of international cooperation should be to reduce the digital divide and manage data gaps and interoperability through multistakeholder consultation, data sharing and technology transfer.

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Note

1. See World Bank indicators at https://data.worldbank.org/indicator.

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Article

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On the role of global change science in sustainable development: Reflecting on Ye Duzheng's contributions

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Abstract

Ye Duzheng was a world-renowned climate scientist and a pioneer of global change science in China and across the world. This paper revisits his ideas on linking global change science to sustainable development and his understanding of orderly human activities, along with his activities in leading research on global change science beginning in the early 1980s. Ye's work has clearly shown that literacy in global change science and Earth system science and the interaction between the social and natural sciences and between policymakers and stakeholders at different levels are essential to sustainable development.

Keywords

Global change, orderly human activities, sustainable development, Ye Duzheng

1. Introduction

Beginning in the 1950s, Professor Ye Duzheng (21 February 1916–16 October 2013) played a key role in the development of modern meteorology in China and was a world-renowned Earth scientist who made many important contributions to atmospheric and climate sciences (Fu, 2017; Hoskins, 2014; Lau, 2017; Lu and Schneider, 2017). Because of his many far-reaching achievements, he was awarded the 2005 China National Preeminent Science and Technology Award – the highest prize for a scientist, for contributions to the development of science and technology by China's central government – and the prestigious International Meteorological Organization (IMO) Prize by the World Meteorological Organization (WMO) in 2003. Professor Ye was the founder of global change science in China and was among the pioneers who initiated and steered research on international global change in the early 1980s (Taba, 2003). Among Professor Ye's fundamental contributions to both basic and applied science in meteorology, the WMO, when bestowing the IMO prize on him, singled out 'the initiation of studies on global change and its relationships with sustainable development, orderly human activities and adaptation to its impacts'.

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Since *Our Common Future* (the Brundtland Report) defined 'sustainable development' as 'development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs' (WCED, 1987), the idea of sustainable development has been widely accepted by the international community. It was reflected in Agenda 21 – a product of the 1992 United Nations Conference on Environment and Development (also known as the 'Earth Summit') held in Rio de Janeiro, Brazil – and was accepted by many countries, including China. Agenda 21 addresses issues regarding social and economic development by focusing on the conservation and preservation of the environment and natural resources. The vitality of the concept of sustainable development was further underlined in the 2030 Agenda for Sustainable Development (Agenda 30), which was implemented by the United Nations in 2015 and announced 17 sustainable development goals. Indeed, the initial conceptualisation of sustainable development in the 1980s was largely related to common concerns relating to environmental deterioration and the depletion of the world's resources owing to rapid industrialisation and overconsumption across the globe. Accordingly, a greater emphasis was laid on policies on social and economic development than on basic science related to the Earth's systems.

On the contrary, the emergence of global change science in the early 1980s was largely associated with increasing concerns about global climate change in the scientific community, among which fears of its effects had been realized even during the 1950s and 1960s (see e.g. Rossby, 1959; Tu, 1961). Although the adverse climatic effects of greenhouse gases, including carbon dioxide, had long been known, the link between the observed trend of warming since the 1850s and the increase in carbon dioxide content in the atmosphere, induced by the widespread use of fossil fuels, was not clear even though some had suspected such a connection (see e.g. Bolin and Eriksson, 1959; Callendar, 1938; Keeling, 1960; Rossby, 1959). That situation persisted until 1979, when the Charney Report provided a rough but science-based estimate that the doubling of carbon dioxide content in the atmosphere may lead to a global average warming of 1.5–4.5°C (Charney et al., 1979). The 1970s ushered in the realisation that it is necessary to consider the climate as a system of atmosphere–ocean–cryosphere–land (i.e. a climate system) to understand the causes of climate change and predict future changes in climate (WMO and ICSU, 1975).

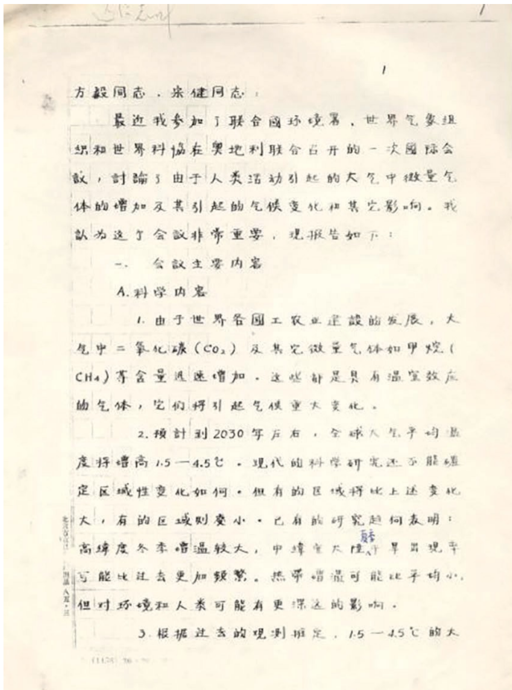
Based on proposals made at the United Nations Conference on the Human Environment in Stockholm, the World Climate Research Programme (WCRP) was launched in 1979, the same year in which the Charney Report was published. Not long after the WCRP was launched, the international scientific community realized the pivotal role of the interactions between global biogeochemical processes and physical processes in global environmental changes. After years of discussion, the International Council of Scientific Unions (ICSU) launched the International Geosphere–Biosphere Programme (IGBP), marking the establishment of global change science or Earth system science (IGBP, 1986). Global change, as defined by the IGBP, encompasses any change in the Earth's environment (changes in the Earth, oceans, atmosphere, biosphere and cryosphere) due to any cause (IGBP, 1986). Professor Ye played a prominent role in both international programmes and proposed insightful ideas to the international community. This paper presents his ideas on the role of global change science in sustainable development and his activities in pursuing those ideas in research projects.

2. Ye's early activities during the establishment of global change science

In 1978, Ye Duzheng was appointed as the director-general of the Institute of Atmospheric Physics at the Chinese Academy of Sciences (CAS), and in 1979 was appointed to a three-member working group (representing China) under the Agreement on Science and Technology Cooperation between China and the United Sates (US), which was signed during Deng Xiaoping's historic visit to the US in January 1979. He also led a delegation of Chinese meteorological scientists to the US in September 1979. In 1981, Ye was nominated as the vice-president of

Figure 1. Ye Duzheng (third from right in the second row) at the 1985 Villach Conference on climate change held in Austria.

Note: The photo is provided by Ye Weijiang, the elder son of Professor Ye.



方毅同志，宋健同志：

最近我参加了联合国环境署，世界气象组织和世界科协在奥地利联合召开的一次国际会议，讨论了由于人类活动引起的大气中微量气体的增加及其引起的气候变化和其它影响。我认为这个会议非常重要，现报告如下：

一、会议主要内容

A.科学内容

1. 由于世界各国工农业建设的发展，大气中二氧化碳（CO_2）及其它微量气体如甲烷（CH_4）等含量迅速增加。这些都是具有温室效应的气体，它们将引起气候重大变化。

2. 预计到2030年左右，全球大气平均温度将增高1.5—4.5℃。现代的科学研究还不能确定区域性变化如何。但有的区域将比上述变化大，有的区域则变小。已有的研究结果表明：高纬度冬季增温较大，中纬度大陆夏季干旱出现可能比过去更加频繁。热带增温可能比平均小，但对环境和人类可能有更深远的影响。

3. 根据过去的观测推定，1.5—4.5℃的大

Figure 2. Ye Duzheng's letter to Fang Yi and Song Jian, written after Ye attended the 1985 Villach Conference.

Note: The photo is provided by Ye Weijiang, the elder son of Professor Ye.

CAS in charge of geoscience research at the academy. Based on his reputation in the international meteorological community as well as his vast experience in international cooperation in science and technology, Ye was selected and served as a member of the Joint Scientific Committee of the WCRP from 1982 to 1988. He led China's delegation to attend the 1985 Villach Conference on climate change held in Austria (Figure 1). After the conference, he wrote a letter (Figure 2) to Fang Yi (then a vice-premier of China's State Council) and Song Jian (then the director of the National Science and Technology Commission). That correspondence led to the establishment of China's National Committee on Climate Research, of which Ye served as chair from 1985 to 1999 (Fu, 2017).

In 1984, the distinguished American atmospheric scientist Thomas Malone, a close friend of Ye, and Juan Roederer from the ICSU visited China and met with Ye under the arrangement of the China Association for Science and Technology. While introducing Chinese scientists to the concept of global change, both Ye and Malone agreed that research activities related to global change should be organized and that younger scientists in China should be involved where this work included the planning of new international research programmes. The ICSU organized the first symposium on global change in Ottawa, Canada. Ye and his colleague, Fu Congbin, were invited to present their position paper, titled 'Climatic change: A global and multidisciplinary theme' (Yeh and Fu, 1985). In it, they discussed the differences and connections between climatic and global changes and pointed out that the decadal and centennial scales should be used as focal timescales for the relevant research. During the symposium, the participants agreed that a new programme in addition to the WCRP (i.e. the IGBP) was needed to integrate the biogeochemical and physical processes of the climate.

The IGBP was formally launched in 1988 by the ICSU after 4 years of preparation. As a pioneer of the programme, Ye was nominated as a member of the special committee for the IGBP (Figure 3). While some in China opposed this endeavour and argued that the country should focus on internal scientific issues, Ye successfully led a group of Chinese scientists to become actively involved in research on global change. The China National Committee of the IGBP was subsequently established, and Ye served

Membership of the Special Committee for the IGBP

J. J. McCarthy (USA), Chairman
R. Herrera (Venezuela), Vice-Chairman
W. S. Fyfe (Canada), Treasurer
T. Rosswall (Sweden), Executive Director
B. Bolin (Sweden)
M.-L. Chanin (France)
P. J. Crutzen (FRG)
E. H. S. Diop (Senegal)
S. Dyck (GDR)
J. A. Eddy (USA)
V. M. Kotlyakov (USSR)
T. Nemoto (Japan)
H. Oeschger (Switzerland)
S. I. Rasool (USA)
J. S. Singh (India)
V. A. Troitskaya (USSR)
B. H. Walker (Australia)
J. D. Woods (UK)
D. Ye (China)

Figure 3. Members of the special committee for the IGBP. Source: IGBP (1989).

as its chairman for its first and second terms, beginning in 1988. By conducting multifaceted research, Ye and his Chinese colleagues made significant contributions to global change science, not only in China, but also at the international level (Fu, 2017; Ye and Chen, 1992). The Global Change Research Centre for Temperate East Asia was established in China in 1994 as the first of its kind and was part of the global change System for Analysis, Research and Training (START) family. Ye was the first director of the centre (Fu, 2017). Research on global change in China has subsequently grown into a long-term, national-level research programme in the first two decades of the 21st century (Zhou et al., 2015).

3. Linking global change science to sustainable development

Before the publication of the third assessment report by the Intergovernmental Panel on Climate Change in 2001, Ye thought it necessary to link global change science, particularly adaptation to the impact of global change, to sustainable development. 'Adaptation' here refers to the adjustment in natural or human systems to respond to expected changes in climate and their effects in order to lessen harm or exploit beneficial opportunities (Taba, 2003). In the early 1990s, the Chinese Government announced that sustainable development was going to be the key national strategy for the country's social and economic development, and China's Agenda 21 was announced soon after the United Nation's Earth Summit held in Rio de Janeiro. However, few people took adaptation to global change seriously at the level of national policy, let alone the detailed measures announced in Agenda 21. This was likely to have been due to the considerable uncertainty in the projection of future climate change, and particularly the even greater uncertainty in predictions of its regional patterns.

Ye thought that the lack of awareness of global change among large segments of policymakers and the general public could pose a significant hindrance to the success of sustainable development in China. Therefore, Ye, together with Professor Zhang Xinshi, a leading botanist and ecologist who had been actively involved in the IGBP, proposed the Xiangshan Science Conference – similar to the Gordon Science Conference in the US. The aim was to discuss ways to link sustainable development to adaptation to global change, and they invited 30 leading scientists in China from the fields of climatology, water resources, water and soil conservation, hydrology, plant ecology, glaciology and estuarine science. I had then just finished my PhD under Professor Ye's supervision, and I was asked to help organize the 3-day conference. Despite the multidisciplinary nature of the conference, Ye ensured that the discussion focused on the relationship between sustainable development and global change and developed a long summary of the dialogue at the end of the conference. The summary was distilled into a paper (Ye and Lu, 2000; Figure 4).

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On Sustainable Development and the Adaptation to the Impact of Global Change

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In this paper, the relationship between sustainable development and the adaptation to the impacts of global change is discussed. With relevant issues in northwestern and coastal areas of China as examples, it is shown that both the problems of adaptation and sustainable development are of a systematic nature.

Keywords: *global change, adaptation, and sustainable development*

I. Introduction

In the domains of geo-sciences and environmental sciences over the last couple of decades, two important problems have come to the fore: global change and sustainable development. Because of their crucial importance to the ongoing existence of humanity, they are widely accepted as the two key issues related to the future of planet earth and of human society per se.

Since its initiation in the early 1980s, global change studies have realized significant achievements. A series of reports by the Intergovernmental Panel on Climate Change (IPCC) show that in general people have got some basic knowledge about the future trends of global change, though some inevitable uncertainties still exist. This basic knowledge includes such facts as [1]:

(1) During the last 100 years, the global surface air temperature has, on average, risen by 0.3–0.6°C, and in recent years has been recorded as the warmest since the instrumental observations began. It is estimated that the global mean surface temperature will rise by 1–3.5°C in the coming 100 years;

(2) Caused by thermal expansion and melting glaciers, the global mean sea level has risen by 10–25cm during the last 100 years, and is estimated to rise by a further 15–95cm in the next 100 years;

(3) The depletion of the ozone layer has resulted in "ozone hole" in the stratosphere appearing from September to December each year in the Antarctic over the last two decades and the reductions of total ozone in the Arctic zone and middle latitudes.

Global change has the potential to significantly influence the ongoing existence and development of humankind. For example, changes of grassland and cultivatable land, as well as that in the tempo-spatial distribution of water resources; changes in soil moisture as a result of temperature rises and changes of the frequencies and intensity of extreme climatic events in some regions, may exert great influences on agriculture, forestry, animal husbandry and other human activities.

It is imperative, therefore, that ways of adapting to these changes should become a priority for mankind. In effect there are two possible actions that can be adopted: (1) Because the emissions of greenhouse gases and materials depleting the ozone layer are to a large extent anthropogenic, humanity should reduce these emissions to mitigate the man-made pressure on global change. In fact, this has partly been the common action of the international society mirrored by the appearance of the Montreal Protocol and the United Nations Framework Convention on Climate Change. This is so-called the 'Mitigation' of the global change. (2) Even if the mitigation activities are fully adopted, the main trend of global

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Figure 4. The first page of the paper by Ye and Lu (2000) on sustainable development and global change.

In the paper, Ye expressed his thoughts on the close linkage between global change science and sustainable development. He claimed that adaptation to global changes must follow the principles of sustainable development; that is, society as a whole must alter its unsustainable lifestyle and style of economic development. Otherwise, adaptation for the sake of only temporary or local interests may damage the environment and lead to even more destructive global change. Similarly, sustainable development will not achieve its goals without taking into account future global changes in climate.

Ye and Lu (2000) also analysed the systematic nature of sustainable development and adaptation to global change, first based on general principles and then by considering the impacts of such changes on the shortage of water resources in north-western China and the rise in levels in the Yangtze River delta as two examples.

Just as the emergence of global change science is based on the understanding that the Earth as a whole is a system composed of different, mutually interactive components, adaptation to the impacts of global change must also be systematic, transcending the boundaries between regions, organisations and business sectors. Otherwise, the situation may well worsen, and adaptation cannot be successful if each region, organisation and business sector considers only its own interests (Ye and Lu, 2000). Similarly, sustainable development should be systematic. While sustainable development goals could be set up for different regions as well as different social and economic sectors, the success of sustainable development depends on coordination among those different regions and sectors. Indeed, the inexorable trend towards regional and global economic integration succinctly demonstrates the systematic nature of sustainable development. Ye and Lu (2000) claimed that ‘if they [different regions and social/economic sectors] think of themselves as part of the whole, co-operating with each other – even making sacrifices where necessary – will benefit the whole overall’. Indeed, ‘only the sustainable development of the system as a whole can really be sustainable’.

4. On the concept of ‘orderly human activities’

As stated in Ye and Lu (2000), global change, including the trend of global warming and environmental deterioration, has been largely caused by human activities, such as the excessive use of fossil fuels, overcultivation, overgrazing and large-scale deforestation. On the multidecadal to centennial timescales, anthropogenic changes in the climate and the environment around the globe are nearly the same as, or even larger than, naturally driven changes (Taba, 2003; Ye and Lu, 2000). That understanding prompted the idea of ‘orderly human activities’, which were defined by Ye and his colleagues as human activities that can ensure that the life-supporting environment as a whole is maintained without notable degeneration, or even with some improvement, while meeting the demands of socioeconomic development (Ye et al., 2001). It is clear that this definition is based on the principle of sustainable development. That is to say, sustainable development is not only the goal of orderly human activities but is also the criterion used to determine whether large-scale human activities are orderly (Fu, 2017; Ye and Dong, 2010).

Ye et al. (2001) discussed in detail the characteristics of orderly human activities, including their goal towards sustainable development, their hierarchical nature, systematic nature and scale effect.

Participants in orderly human activities include not only governments and policymakers at different levels, Ye et al. (2001) claimed, but also the scientific community, the public and other stakeholders. In particular, Ye et al. (2001) emphasized the importance of scientific research in promoting environmental awareness in the policymaking process of governments, and in encouraging mutual feedback and interaction between policymakers and stakeholders. Indeed, literacy in global change science may well contribute significantly to integrating and coordinating the activities of different participants to achieve the goals of sustainable development.

Ye et al. (2001) further put forward an approach to research on orderly human activities that should be closely integrated with the policymaking process and activities of stakeholders at different levels. They stressed that interdisciplinary cooperation between the social sciences and natural sciences is pivotal to the success of such research and that demonstration areas of orderly human activities that coordinate policymakers, scientists and stakeholders should be established.

5. Summary

Ye Duzheng was a world-renowned climate scientist, the founder of global change science in China and a pioneer of global change research. This paper has revisited his leading ideas on linking global change science to sustainable development and his views of orderly human activities, together with his work in leading global change research in China, beginning in the early 1980s. It is clear from Ye's work that literacy in global change science and Earth system science and the interaction between the social and natural sciences and between policymakers and stakeholders at different levels of governance are essential to achieve sustainable development. Global change science has moved to a new phase of 'future Earth' research (Zhou et al., 2015). Understanding the Earth's systems, including human activities, as a whole and exploring the relation between global change and sustainable development are expected to contribute to a better future for the planet and the welfare of its inhabitants.

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